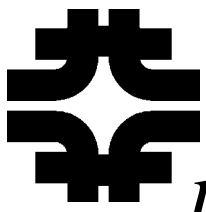# *Exploring the New World of Neutrino Physics*
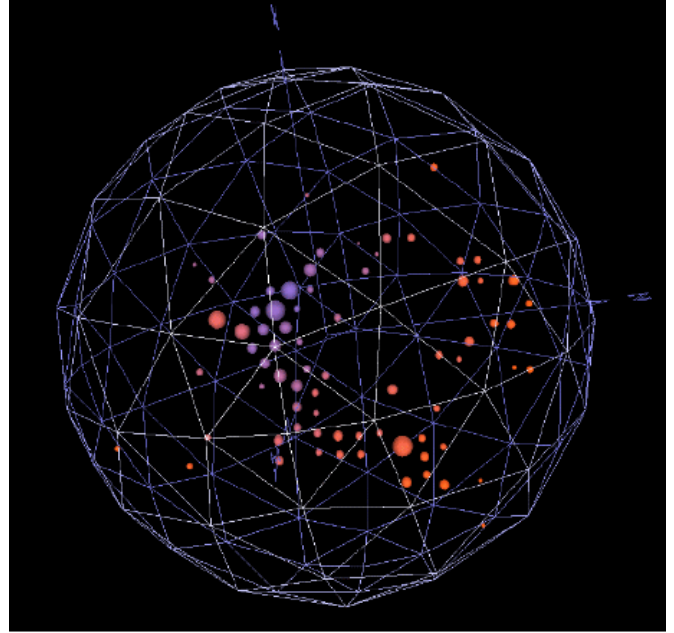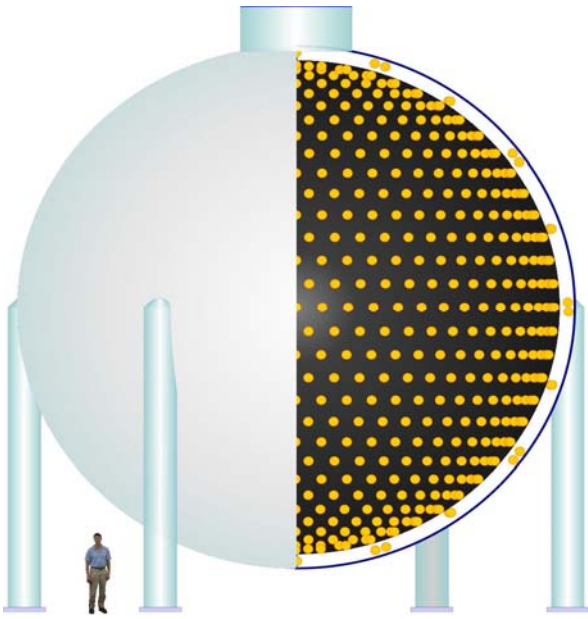
Rob Plunkett

Fermilab Academic Lecture Series

Section III - Spring 2006

Lecture 3 - MiniBoone, the reactor approach, and "if..."

An appearance experiment using ν_μ at high values of Δm^2
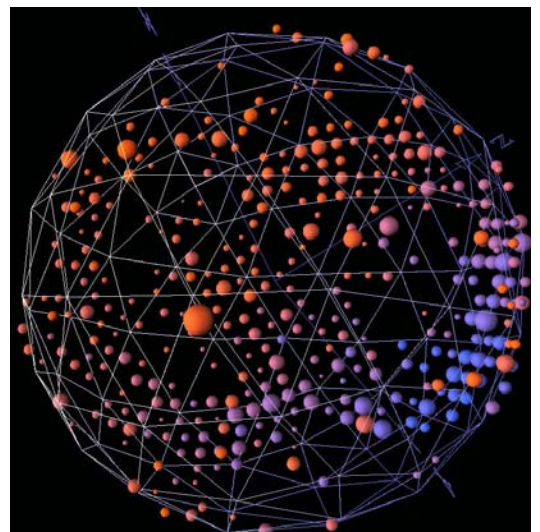## *- MiniBoone -*

e from μ decay candidate.
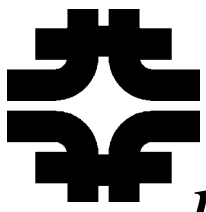
Ragged outer edge of ring from scattering, brems

12 m sphere, 950 K liters of oil.

1280 PMT's - 8" diameter

Cerenkov and Scintillation light

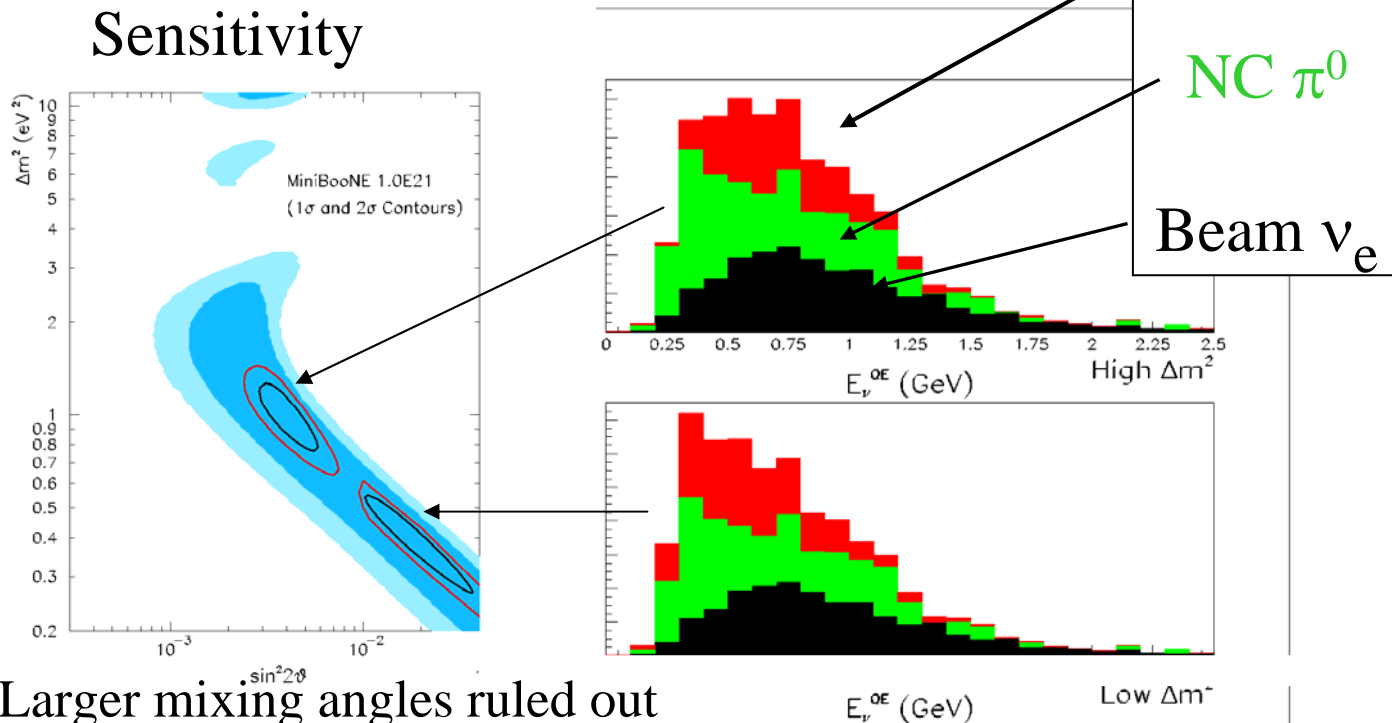π^0 candidate –
overlapping rings,

An appearance experiment using ν_μ at high values of Δm^2

Check/confirm LSND oscillation signal at Fermilab Booster

Different systematics from previous experiment

–L=540 m ~10x LSND

–E~500 MeV ~10x LSND

Sensitivity

ν_e signal

NC π^0

Beam ν_e

MiniBooNE 1.0E21
(1σ and 2σ Contours)

E_ν^{QE} (GeV)   High Δm^2

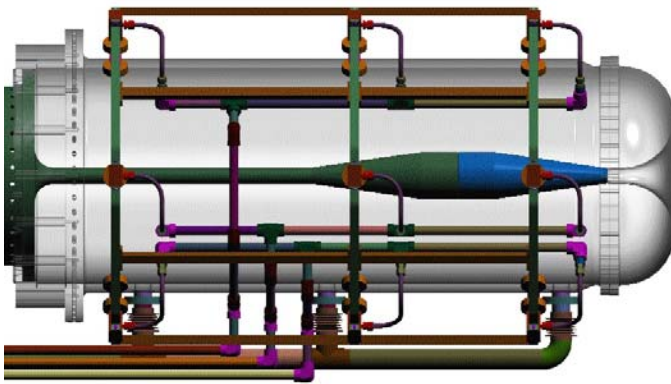E_ν^{QE} (GeV)   Low Δm^-

Larger mixing angles ruled out in the 80's
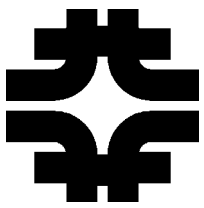
Intense Booster Neutrino Beam
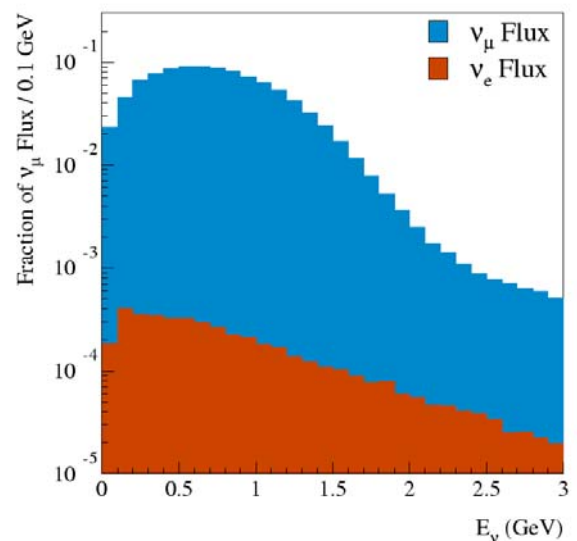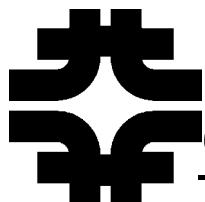
MiniBoone horn showing interior
conductor structure

Horn focusing of secondary
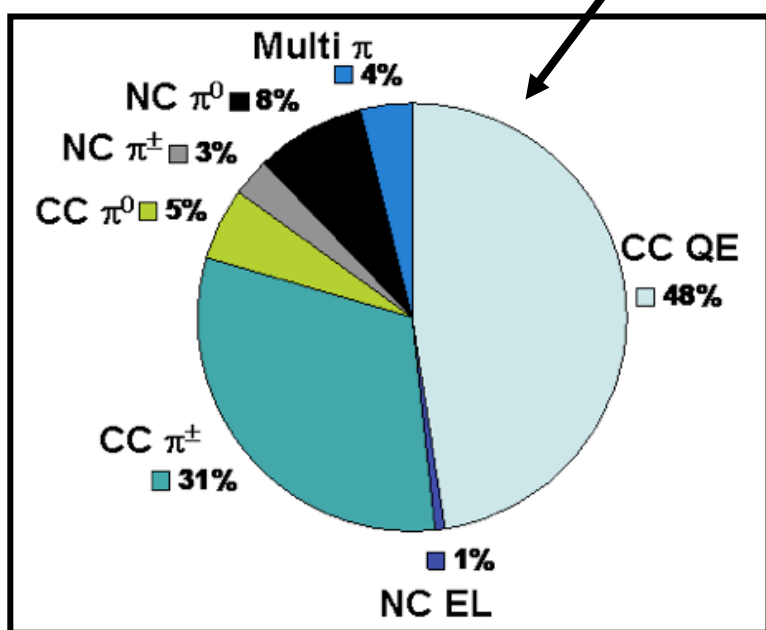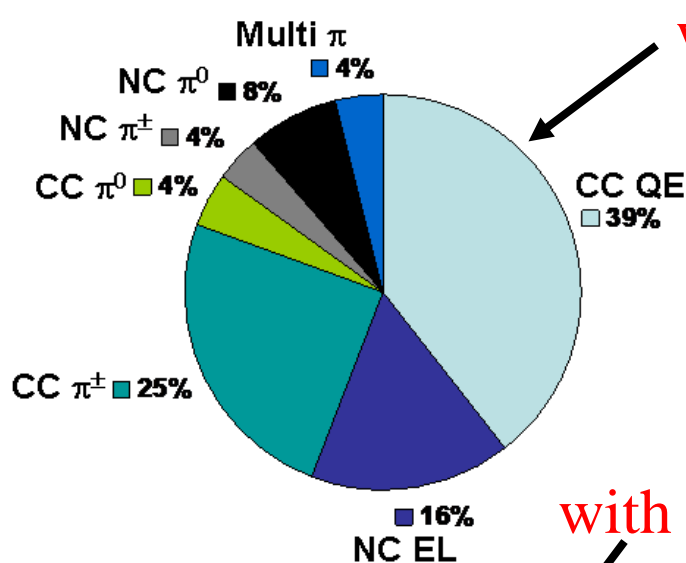beam increases ν flux by
factor of ~6

8 GeV protons from Fermilab Booster
50 m decay pipe region
500 m earth shielding

Proton flux from
3×10^{16} to 7×10^{16}
protons/hour

Composition of MiniBoone ν_μ beam events

with no selection cuts

Multi π ■ 4%
NC π^0 ■ 8%
NC $\pi^\pm$ □ 4%
CC π^0 ■ 4%
CC QE □ 39%
CC $\pi^\pm$ ■ 25%
16% NC EL

with simple veto, energy cuts

Multi π ■ 4%
NC π^0 ■ 8%
NC $\pi^\pm$ □ 3%
CC π^0 ■ 5%
CC QE □ 48%
CC $\pi^\pm$ ■ 31%
1% NC EL

- **48% CC QE**
- **31% CC π^+**

- **8% NC π^0**
- **5% CC π^0**
- **3% NC $\pi^{+/-}$**
- **4% multi-π**
- **1% NC elastic**

Courtesy G. Zeller
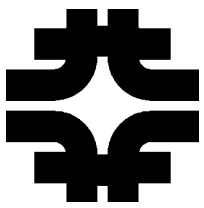
Event topologies in the MiniBoone detector

e

ν_e e^-

W

n

p

fuzzy from scattering

μ

ν_μ μ^-

W

n

p

fillilng in from slowing down

π^0

ν_μ ν_μ

Z

n Δ^0 π^0

p

overlapping
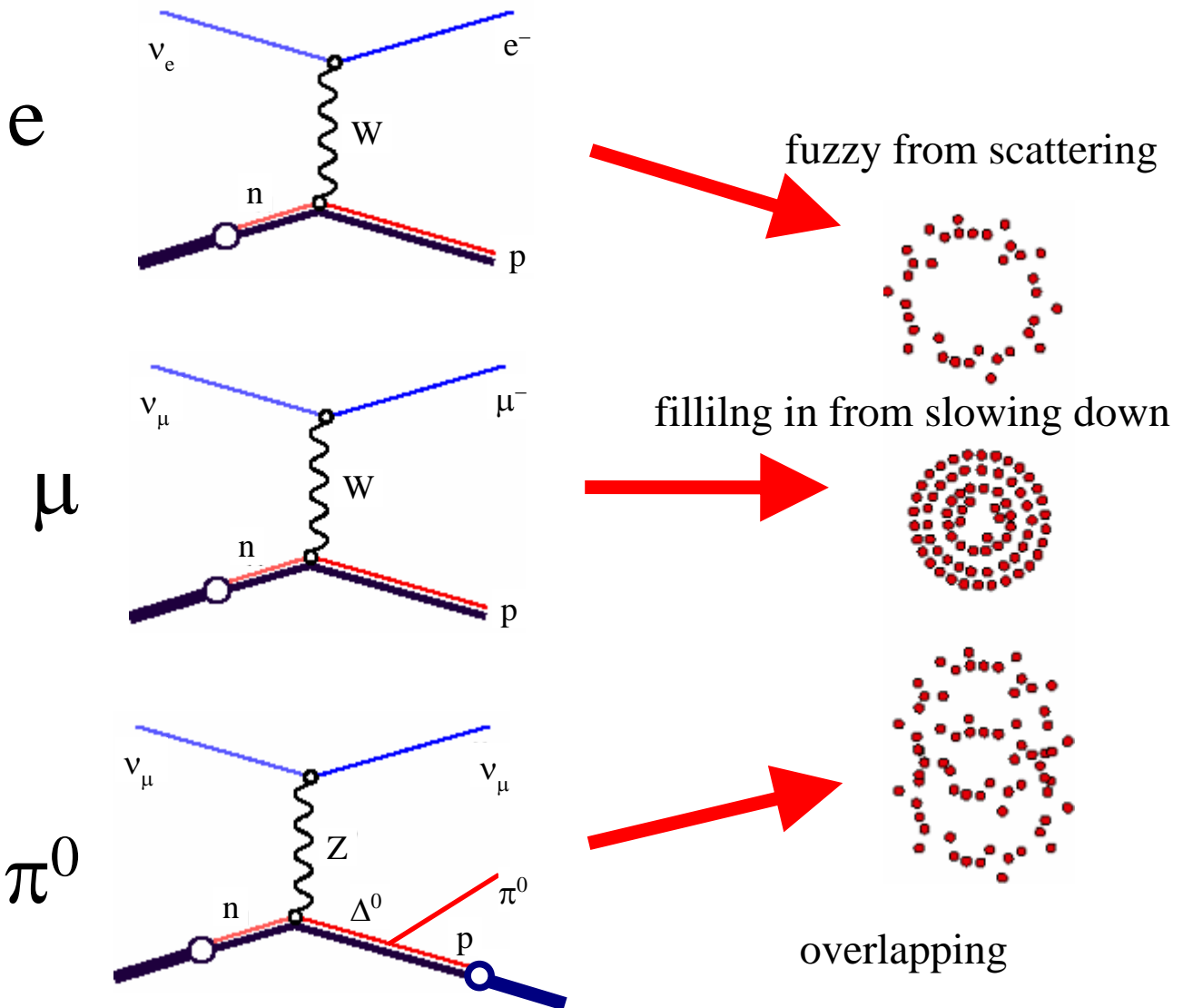
Graphic from S. Brice
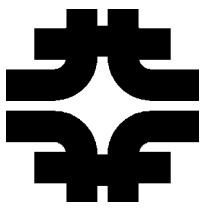
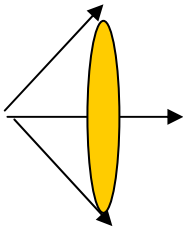# Example of simple detector analysis - μ/e discrimination
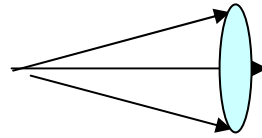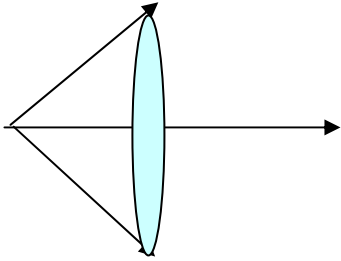
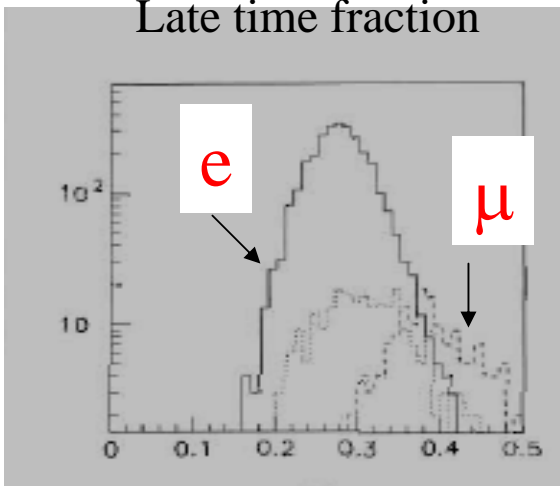Muon - long range (late hits), cone fills in as muon slows.

recall Chernkov angle

$$\cos\theta = \frac{1}{\beta n}$$

Electron - short range (prompt), most light in outer part

Late time fraction

Large angle light fraction
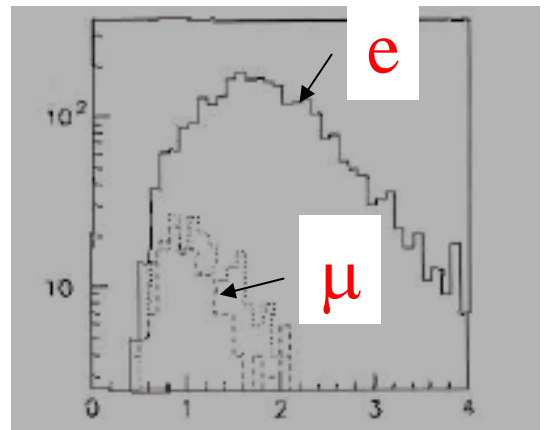
Note: this is a very old illustration of how this can be done. MiniBoone now uses likelhood analysis techniques
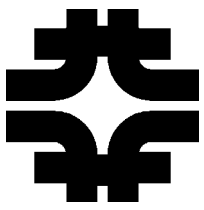
MiniBoone Cross-section Data

(J. Monroe)

QE event spectrum reconstructed using kinematics

$$E_\nu^{QE} = \frac{2M_pE_\mu - m_\mu^2}{2(M_p - E_\mu + p_\mu\cos\theta_\mu)}$$

Single π^+ cross-section normalized by QE calculation
(flux not known well)

(J. Monroe, M. Wascko)
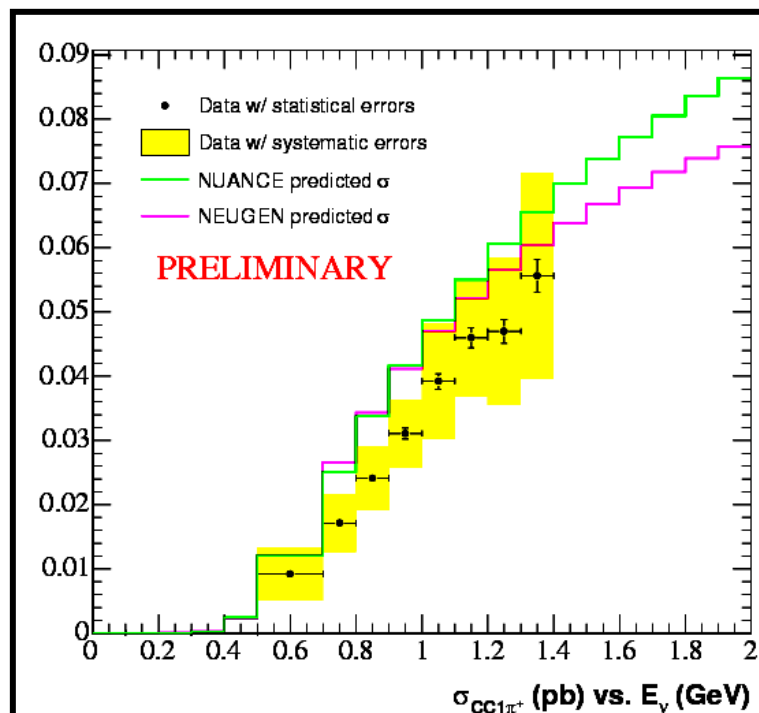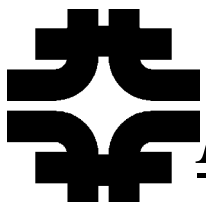
Reactor Experiments - sooner and later

Reactor experiments provide an alternative route to measurement of $\sin^2 2\theta_{13}$.
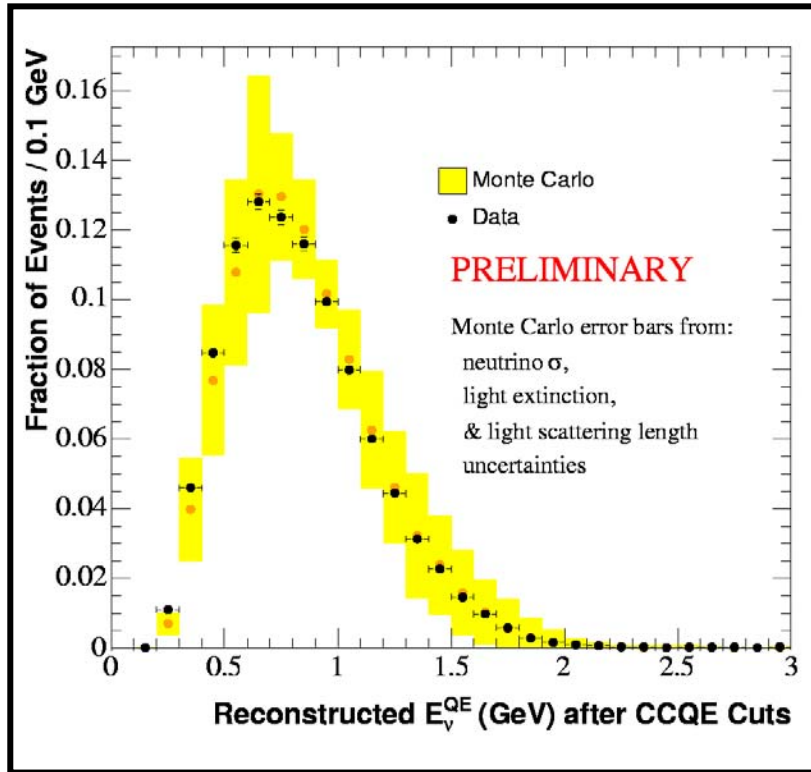
$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{atm} L/4E) + O(\text{solar})$

Free from CP, hierarchy assymetries.

Disappearance experiments at modest baselines

Ballpark: *$<E\nu> \cong 3$ MeV at 1 km gives $L/E = .003$*

comparable to MINOS

Reaction

$$\overline{\nu}_e + p \rightarrow n + e^+$$
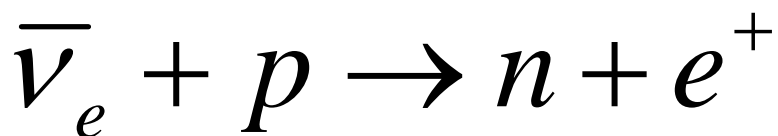
Detect via annihilation γ, followed by delayed γ from n-capture on nucleus
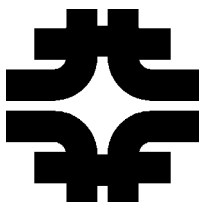
Reactor Experimental Landscape
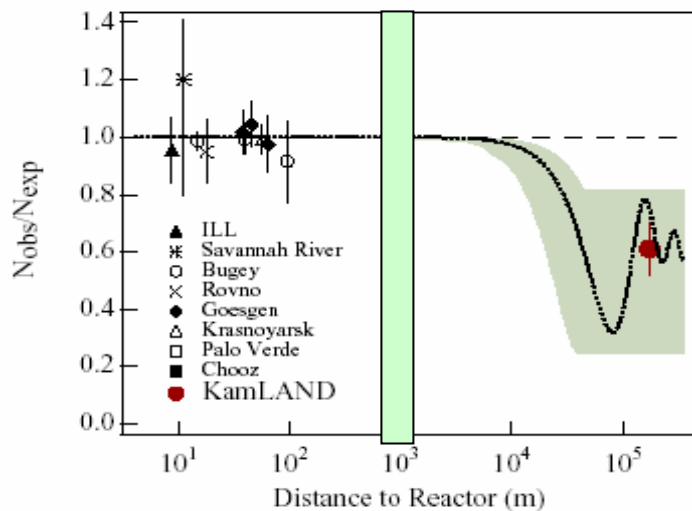
KamLAND sees a 40% deficit/shape at 200km related to Δm^2_{12}

Search for a 1-5% deficit/shape at ~1 km related to Δm^2_{13}

a) $\overline{\nu}$e interactions/MeV-day
b) $\overline{\nu}$e Flux (10^8/MeV-s-cm^2)
c) $\sigma(E\nu)$ (10^{-43} cm^2)
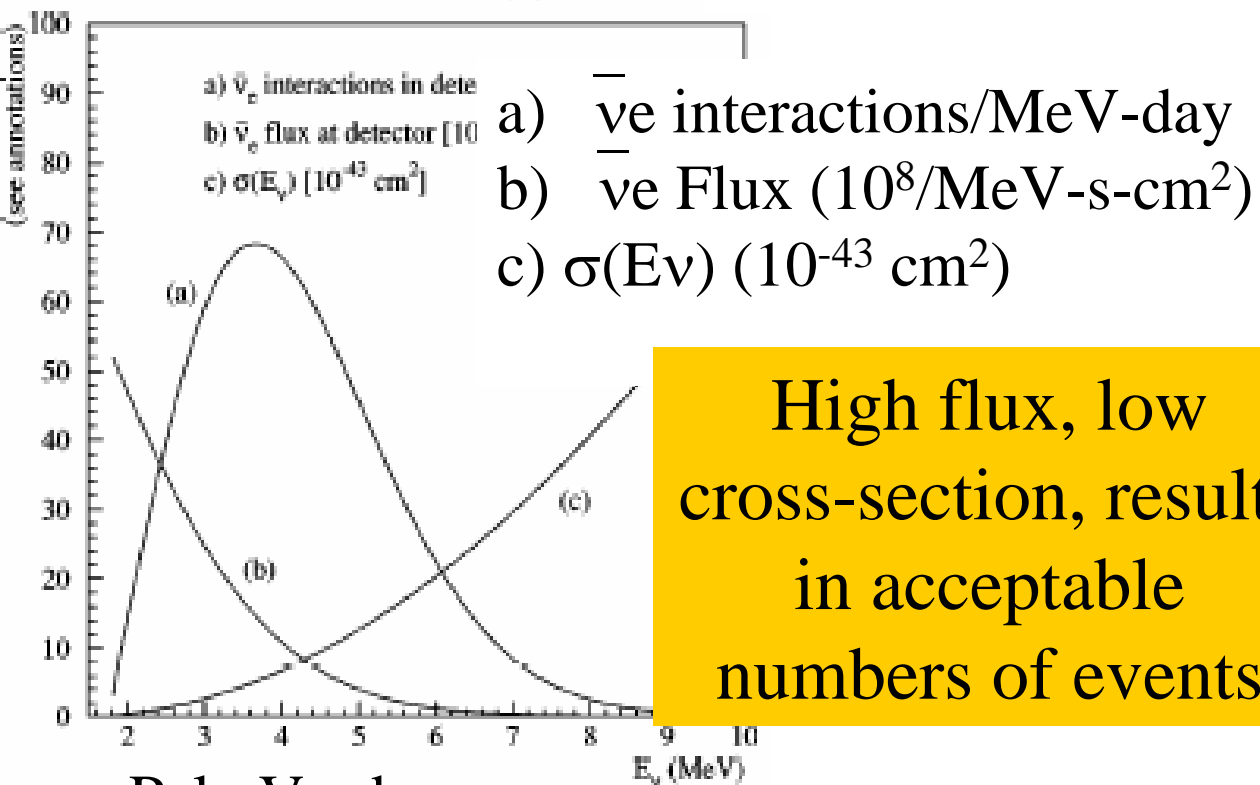
High flux, low cross-section, results in acceptable numbers of events

Palo Verde

Courtesy KamLand, Palo Verde, Reyna

∓ from Palo Verde
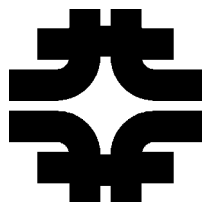
Near term for reactor θ_{13}
Double Chooz

Currently world's best limit $\sin^2 2\theta_{13} < 0.14$

Improve by adding near detector, increasing mass of detector(s) 5T –> ~10T

Reactor Power substantially increased.
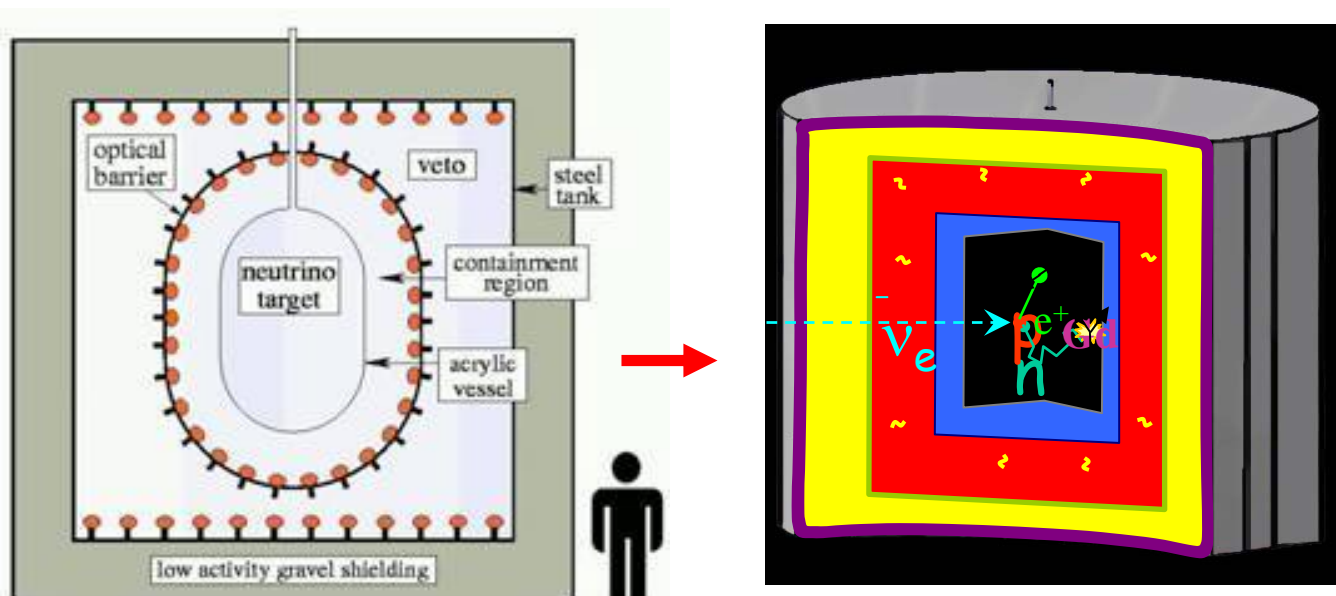
Distances : Near 100-200m   Far: ~1 km
Depths: Near 30-40m   Far: ~100 m

Exposure: 12 GW-T-year ==> 200-300 GW-T-year

Events: 2700 ==> 40K

Double Chooz Sensitivity

Double Chooz Sensitivity (5 year run)

Double Chooz

$\Delta m^2 = 0.002$

$\Delta m^2 = 0.002$

$\Delta m^2 = 0.003$
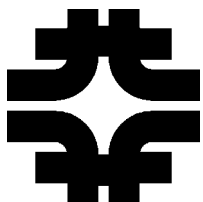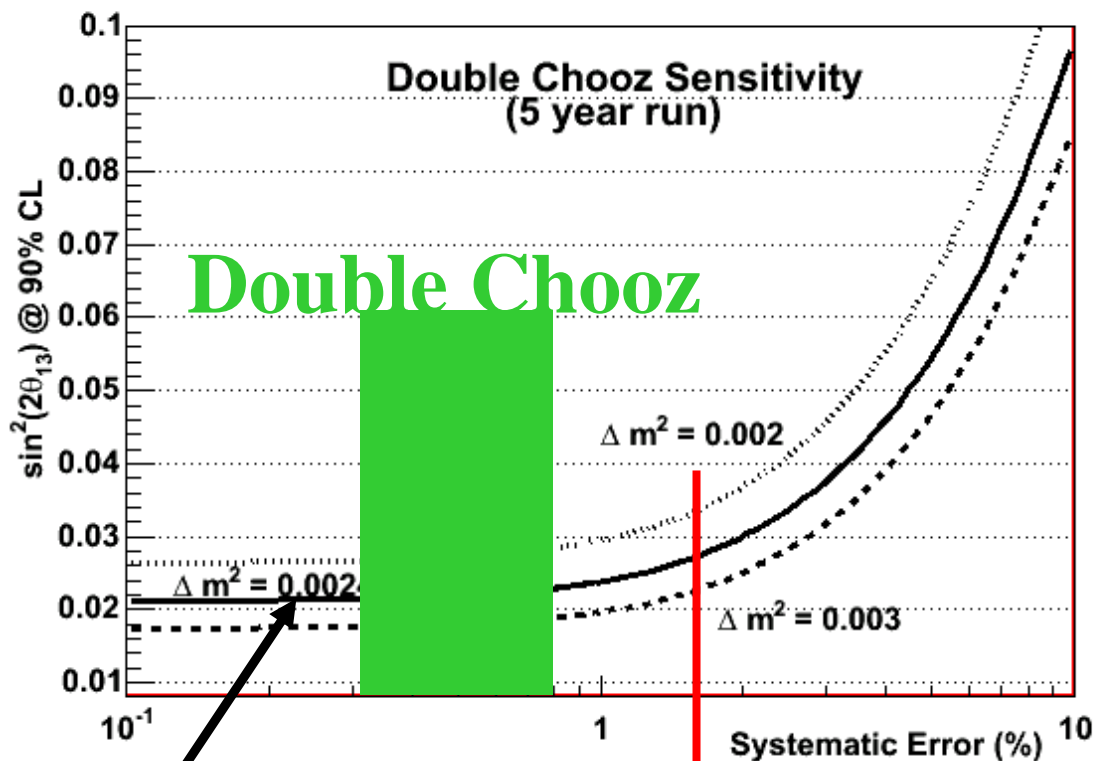
statistical limit

Original Chooz Detector Error

sin^2(2θ_{13}) @ 90% CL

Systematic Error (%)

	Chooz	Double-Chooz
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—
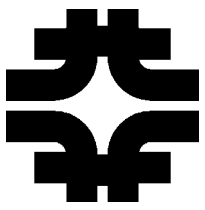
Background reduction in DoubleChooz
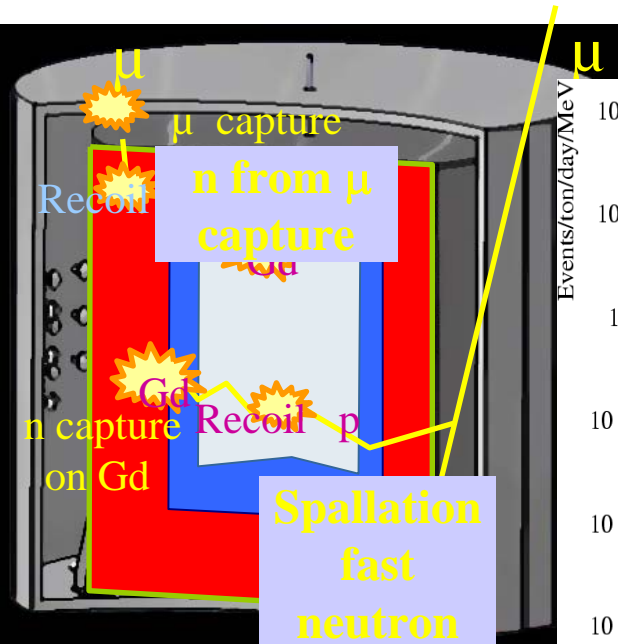
Typical Spectra (Braidwood)

Spallation Isotopes

^{40}K

^{238}U

^{232}Th

Events/ton/day/MeV

Singles Rate Energy Spectrum

Assuming KamLAND concentrations of ^{40}K, ^{232}Th and ^{238}U and 450 mwe

Plot made by Hannah Newfield-Plunkett
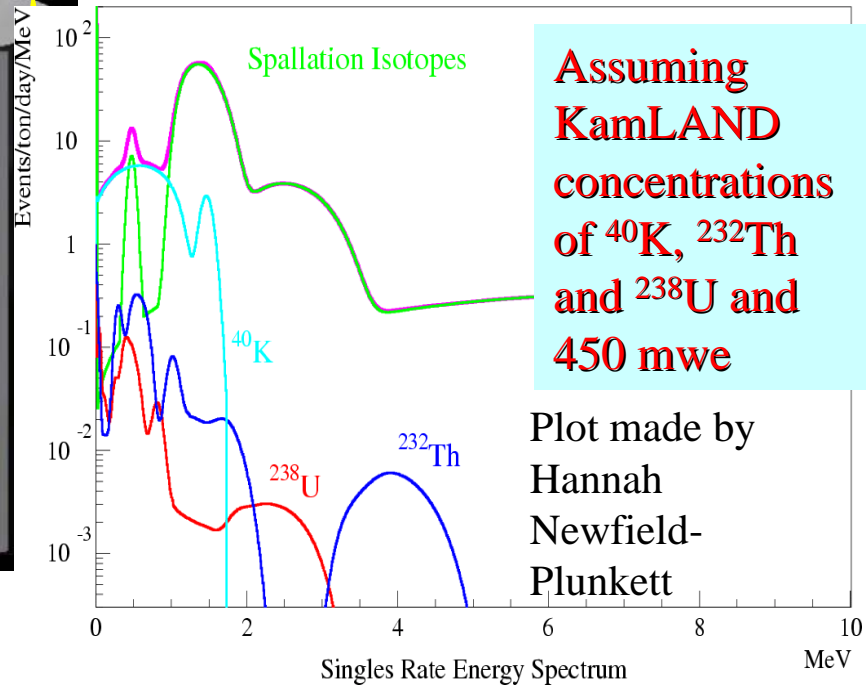
Background coming from radioactive materials, cosmic sources.

Spallation neutrons from μ, direct β-emitter creation

Control via detector design, reactor-off comparison with simulation

Expect total background subtraction systematic ~1%
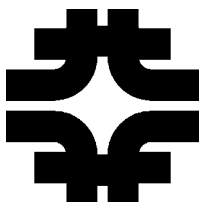
Next Generation Reactor Experiments - Braidwood and/or Daya Bay

Main avenues of improvement
- Increased Mass
- Depth
- Intercalibrated detectors

Braidwood, IL
4 x 65 T detectors
460 mwe (both)

Daya Bay, China
8 x 20 T detectors
1000 mwe (far)

Sensitivity and Systematics

Move detectors next to one another to intercalibrate

Reactor Core

Moving Detector

Elevation (m)

| Glacial Till |
| Pennsylvanian |

Near | Maquoketa Shale | Far
Shaft | | Shaft

Galana

Platteville
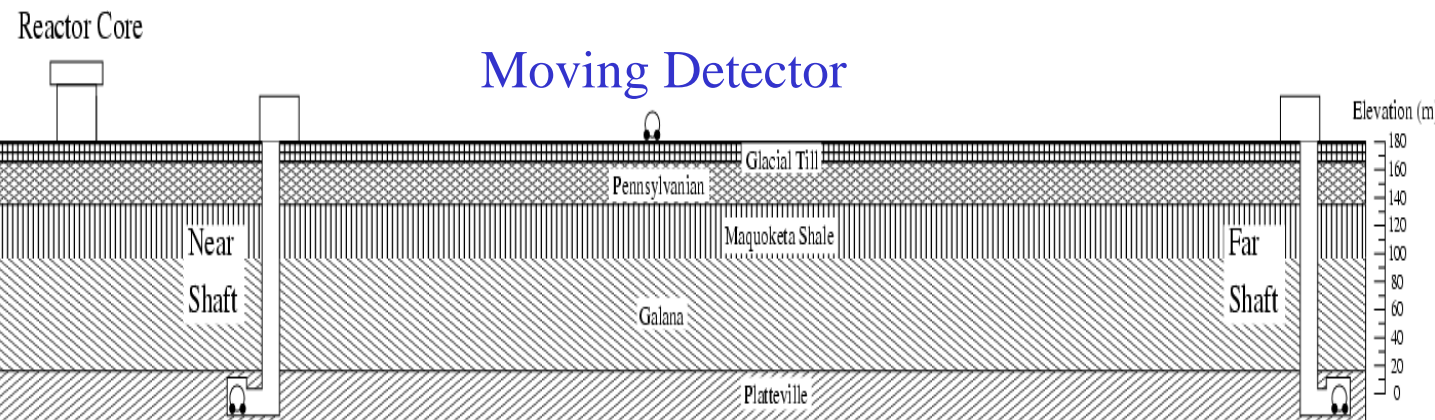
Braidwood detector moving scheme (vert. exaggerated)

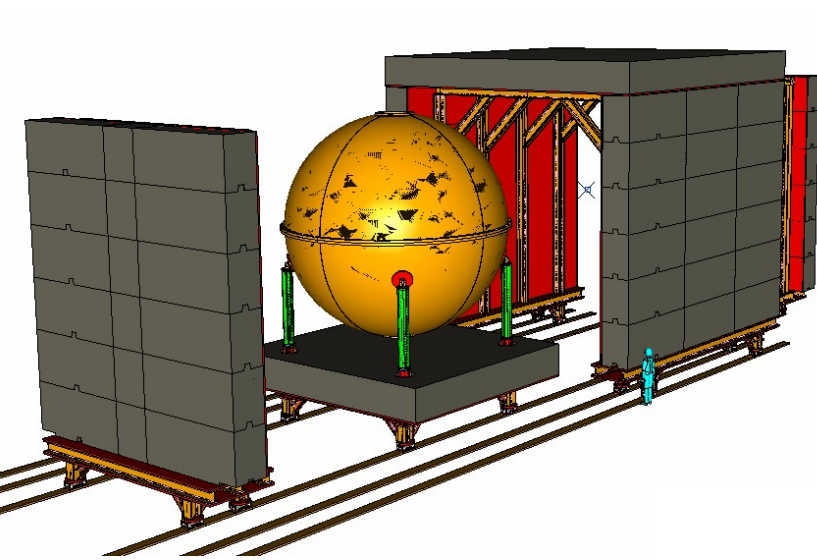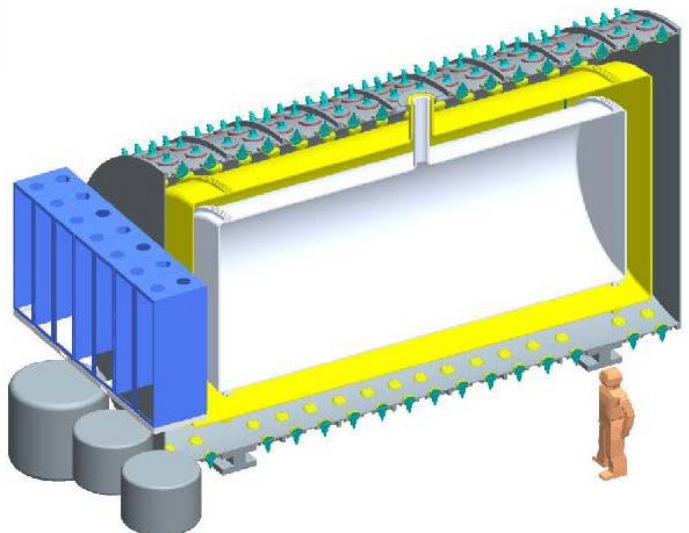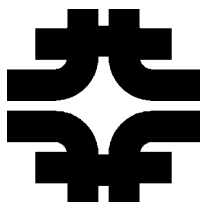**Braidwood estimate for 3 years run**
90% CL limit at $\sin^2 2\theta_{13}$ < 0.005
3 σ discovery for $\sin^2 2\theta_{13}$ > 0.013

Chooz
Daya Bay
Fast

$\Delta m^2 \ (\times 10^{-3} \ eV^2)$

Daya Bay Sensitivity

$\sin^2 2\theta_{13}$
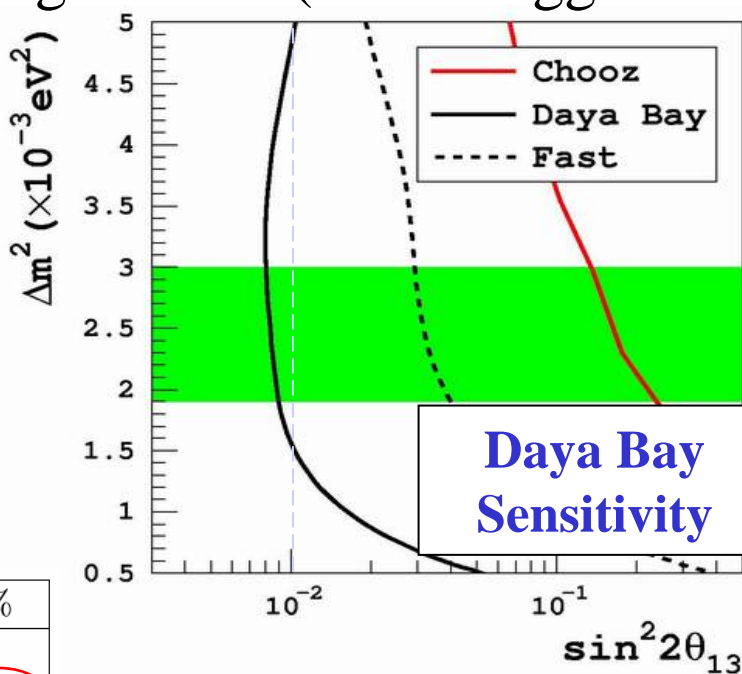
Source of Uncertainty	%
Relative Normalization for each Near/Far Detector Pair	0.3
Far Detector Statistics	0.2
Near Detector Statistics	0.04
Backgrounds	0.15

2 x better than Double Chooz

6 x better than Double Chooz (300 mwe vs 450 mwe)
50% better than Daya Bay ? (450 mwe vs 1000 mwe)
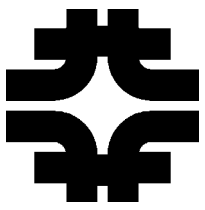
Advanced R&D to increase sensitivity

- We've seen that NoVA, T2K, MiniBoone and reactor experiments map a challenging near-future.

- Physics of CP and mass hierarchy is very hard at low $\sin^2 2\theta_{13}$

- In this final section, we will examine more speculative ideas about how to go beyond the next generation
  - Confront essential challenge of physics of oscillating neutrinos: Rate vs. Distance

- Improvements in backgrounds for low-rate measurements
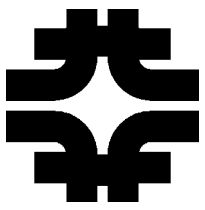
How to get more neutrinos to study.

- Can increase detector mass
  - Hyper-K as an example
  - Multiple detectors
- Can increase number of protons in a conventional facility
  - Fermilab upgrades
  - J-Parc upgrades
- Can try something entirely new
  - Neutrino factory from muon decay
  - Beta-decay based beams

Need for flexibility as the future is not ours to see.
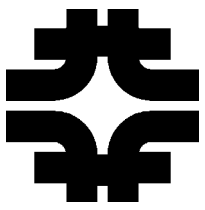
Sidebar - Hyper-K megaton detector

1 MTon Water Cherenkov (like Super-K)
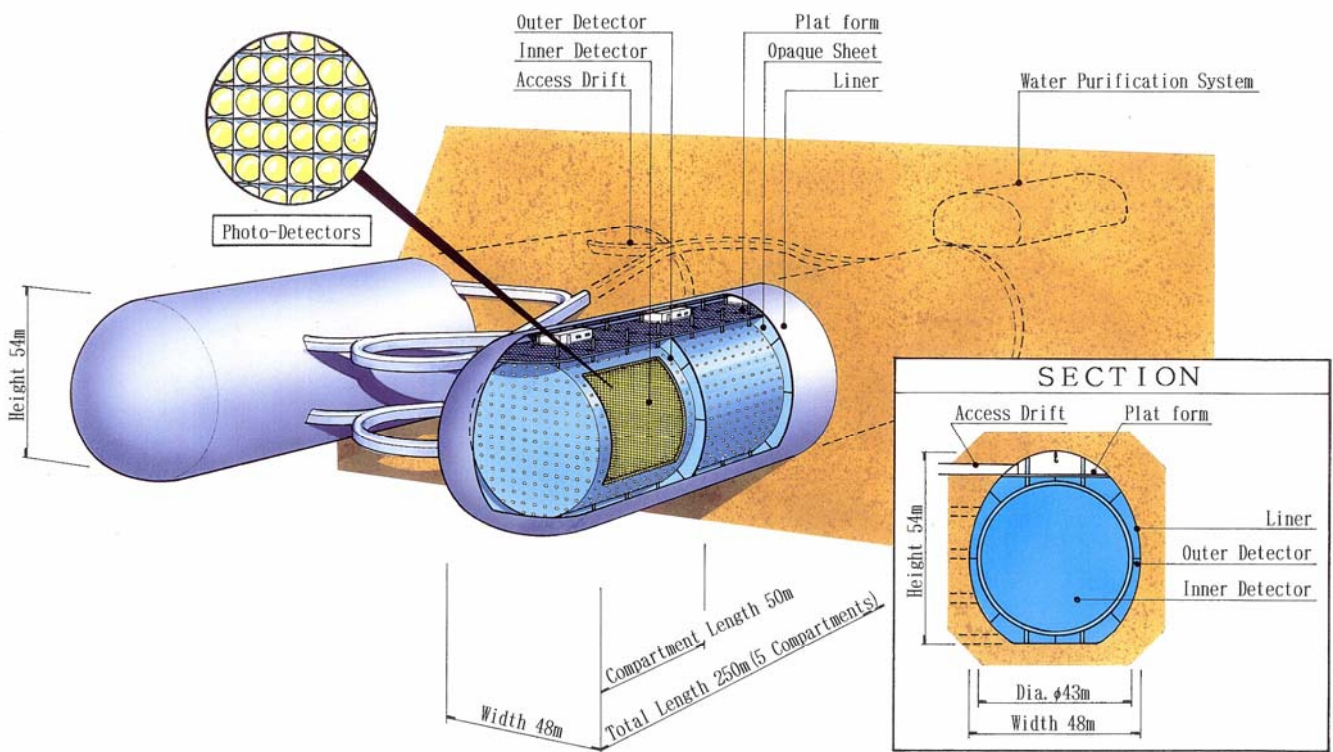0.54 MTon fiducial volume
200 K PMT's

Tunnel shape cavity helps excavation and optimizes detector performance

< 50 m deep for PMT's

Light path < 100 m

Dual cavities allows for staged construction, maintenance
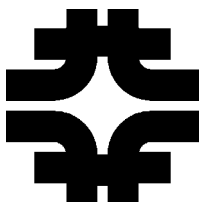
Combining detectors to help in ambiguity resolution
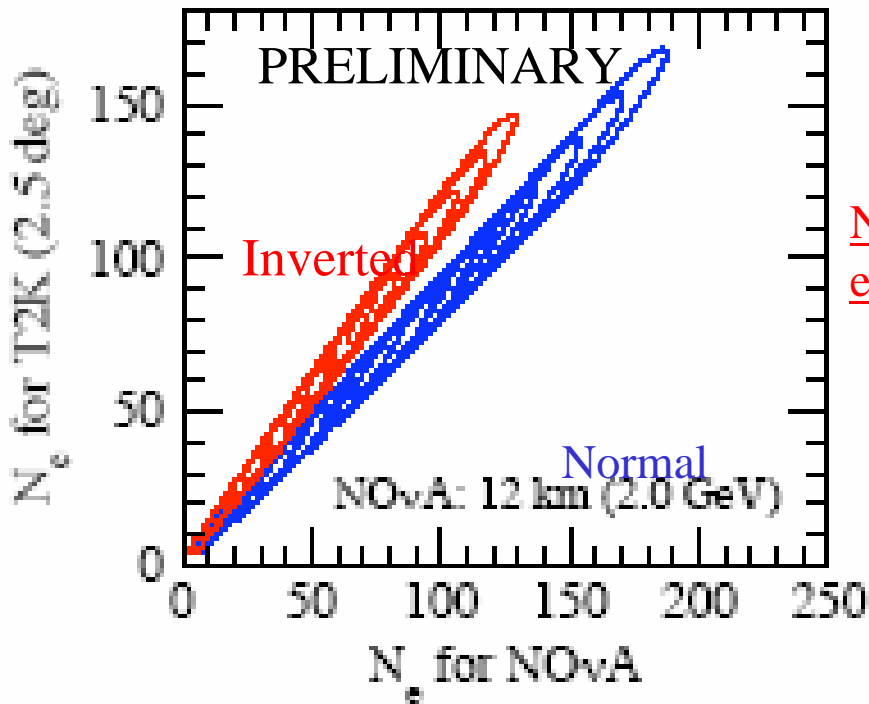
NOvA: 5 years neutrino @ 6.5 x 10^{20}/ year
T2K 5 years @ 0.75 MW

As discussed last lecture, combination of experiments can help with ambiguity resolution.
In this case angles are important, E/L affects width of ratio.

Note that this is mass hierarchy with only neutrinos!

Mena,Minikata,Nonokaw, and Parke, PRELIMINARY
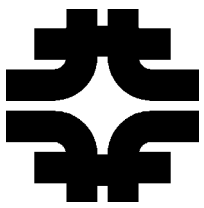
Advantages of a second detector

(Mentioned briefly in Lecture 2 with 30 km off-axis at 710 km)

Upgraded Intensity (25×10^{20}/year)
6 years one detector + 4 years both
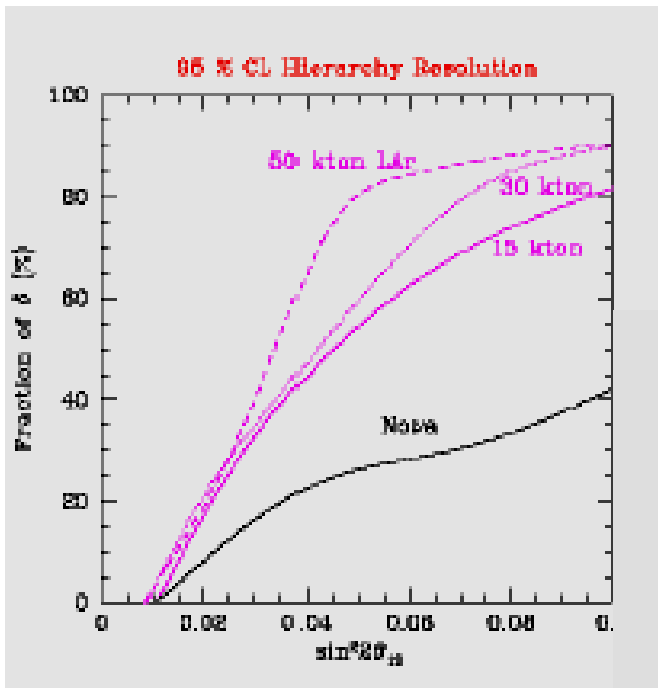
Nominal Intensity (6.5×10^{20}/year)
6 years one detector + 8 years both
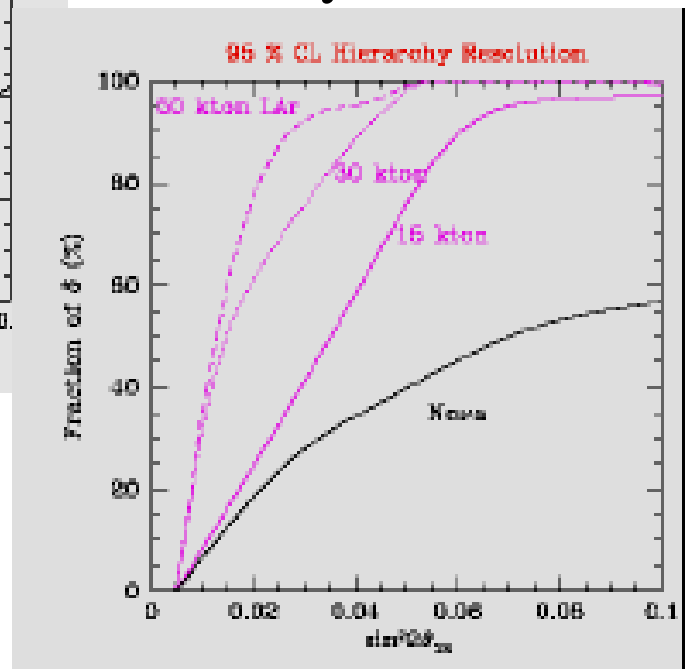
One scenario with a second detector located at 200 km, with 0.7 GeV beam!

Mena, Palomares-Ruiz, and Pascoli, hep-ph/0510182
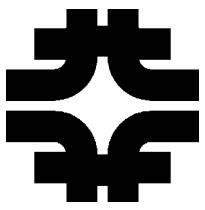
"For best results", 2nd detector should be very efficient.
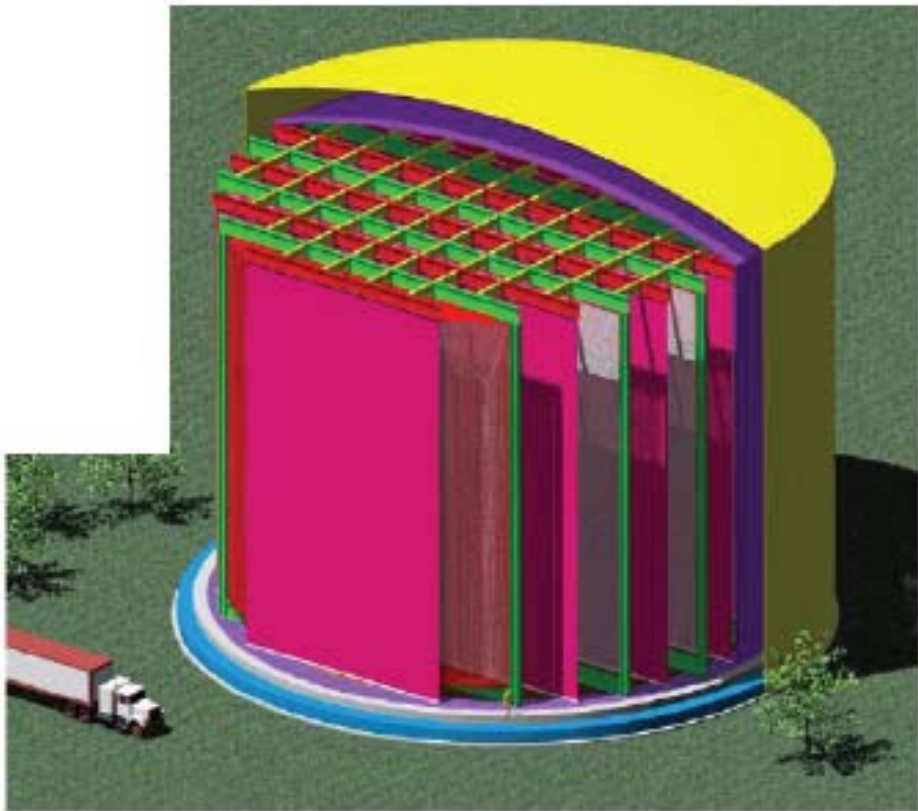
One potential technology is large liquid Argon (LAr) TPC

- Industrial size tanks
- Challenges from purity, noise, long drifts, cost
- Extremely high efficiency (claim ~90%)
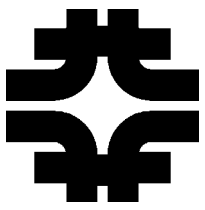
Potential for Korean 2nd Detector

Split fiducial mass in 2 pieces (0.27 MTon each)
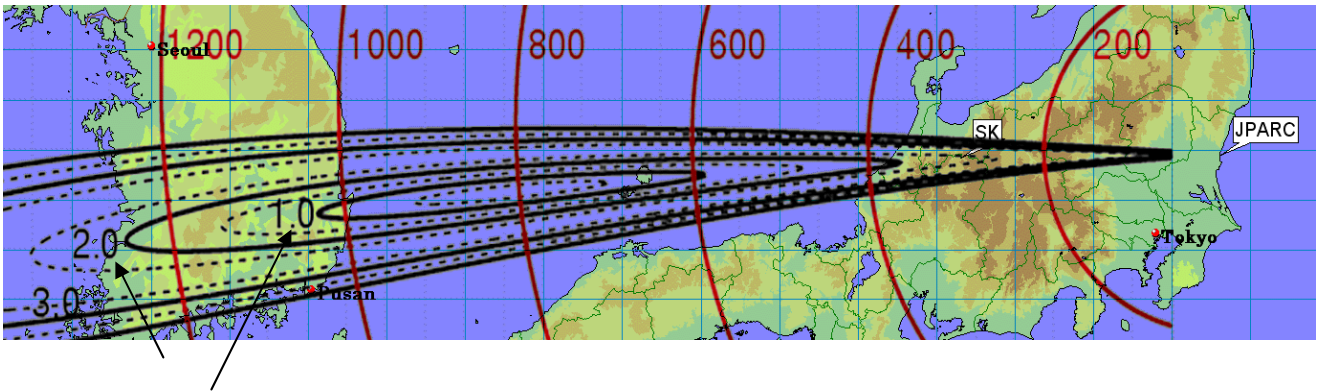
Off-axis angle (degrees) in 3 dimensions

Sensitivity to mass hierarchy

8 years

2σ

3σ

Kamioka + Korea
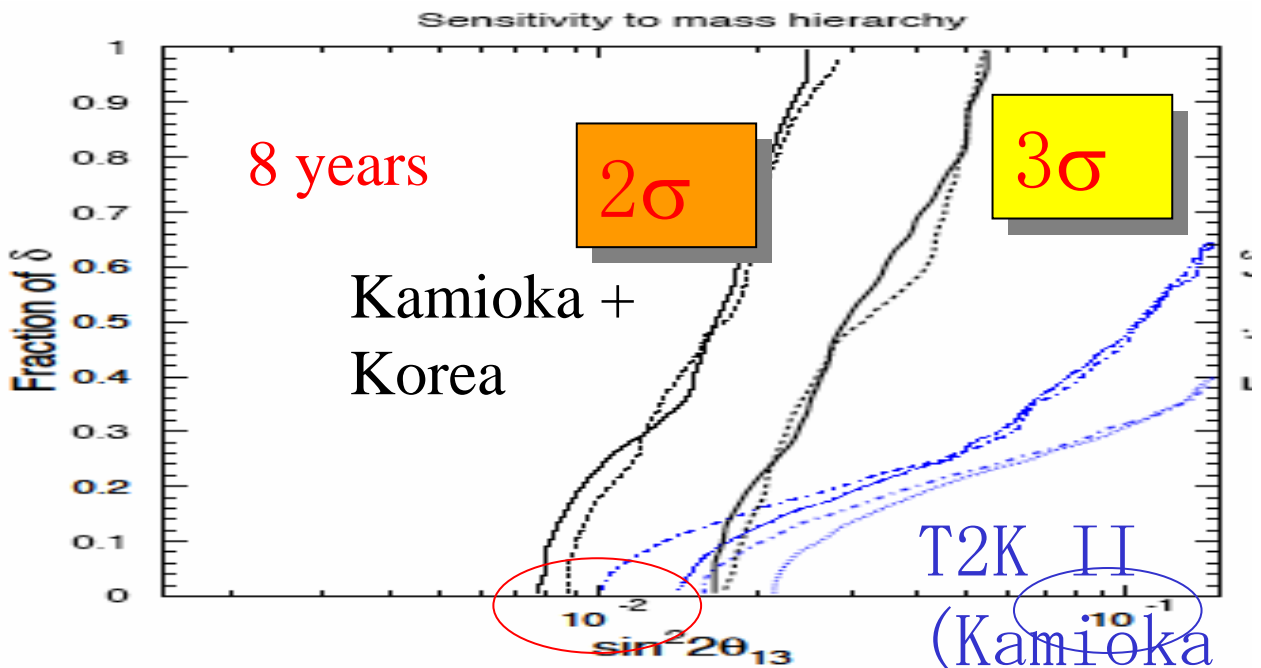
T2K II (Kamioka)

Gives matter effect so that mass hierarchy can be studied

hep-ph/0504026
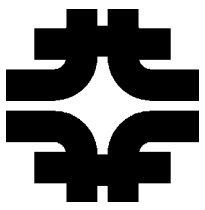
Fermilab's role in providing protons for neutrinos

- The NuMI facility is unique in U.S. and practically world-wide

- Long-baseline, experiments both running and in pipeline

- Lab has both a short-term plan and longer term ideas about making the beam stronger.

- Will not discuss the Proton Driver (a new accelerator here).
  - It's been discussed a lot

- Will discuss two phases of improvements.
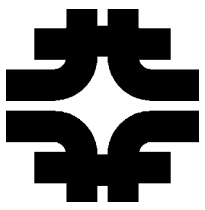
First wave of improvements to Fermilab protons

After the Collider era, the Recycler becomes a proton accumulator.

Run booster feeding Recycler asynchronously (while MR accelerates).

**With 5.4×10^{13} ppp every 1.467 s $\Rightarrow$ 700 kW
with 2×10^{7} effective seconds/year $\Rightarrow$
7.5×10^{20} pot/year**

This basically doubles output of complex NOvA is counting on these protons for first phase of experiment

S. Nagaitsev, E. Prebys, M. Syphers 'First Report of the Proton Study Group', Beams-doc-2178

after A. Marchionni
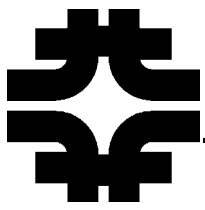
Second wave of improvements to Fermilab protons

We may *also* be able to use the Accumulator in the Anti-proton Source as a proton accumulator
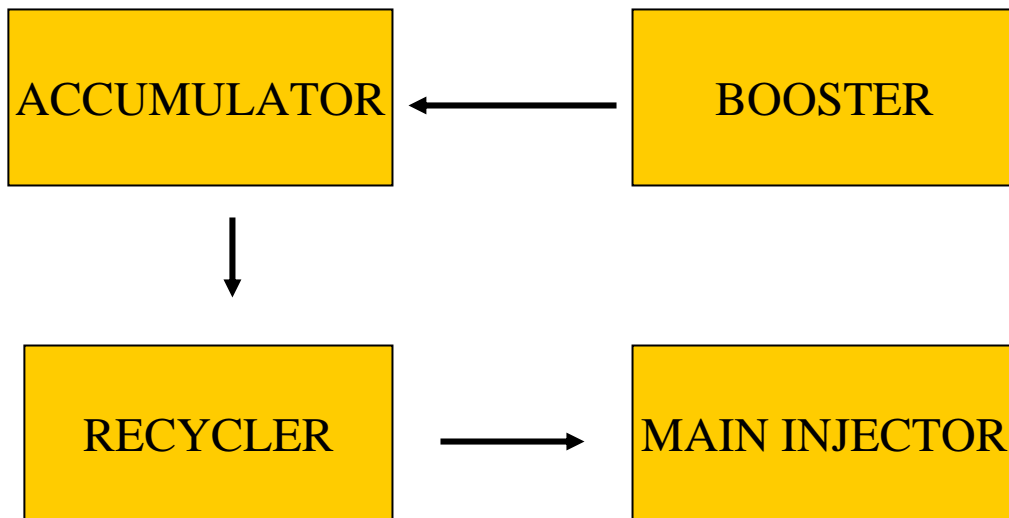
9.5×10^{13} **ppp in MI every 1.6 s**

$\Rightarrow$ **1.1 MW**

$\Rightarrow$ **12×10^{20} pot/year**

60% of a proton driver!

D. McGinnis, Beams-doc-1782, 2138
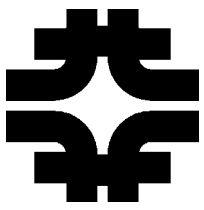
Can a beamline to a large DUSEL detector fit at Fermilab?
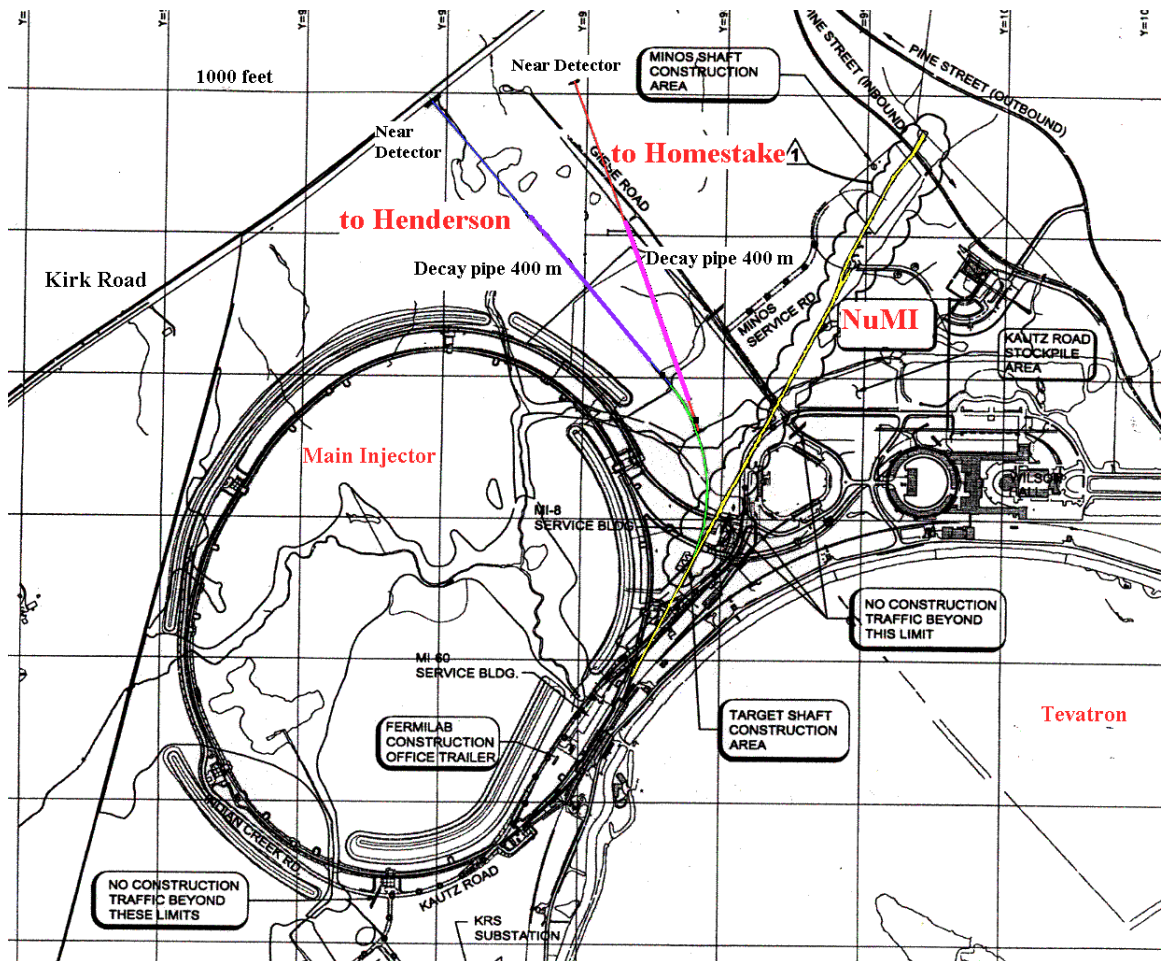
400 m decay pipe for use with low energy beam

Homestake (SD) 1289 km, ~ -6 degrees
Henderson (CO) 1495 km, ~ -7 degrees

W. Smart
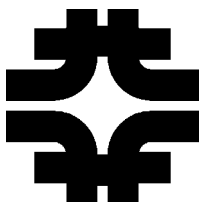
Preferred DUSEL sites in the United States

Homestake
2540 / ~1300 km

FNAL   BNL

Henderson
2770 / ~1500 km

The U.S. DUSEL sites enjoy a natural geographical advantage not present in other potential world sites
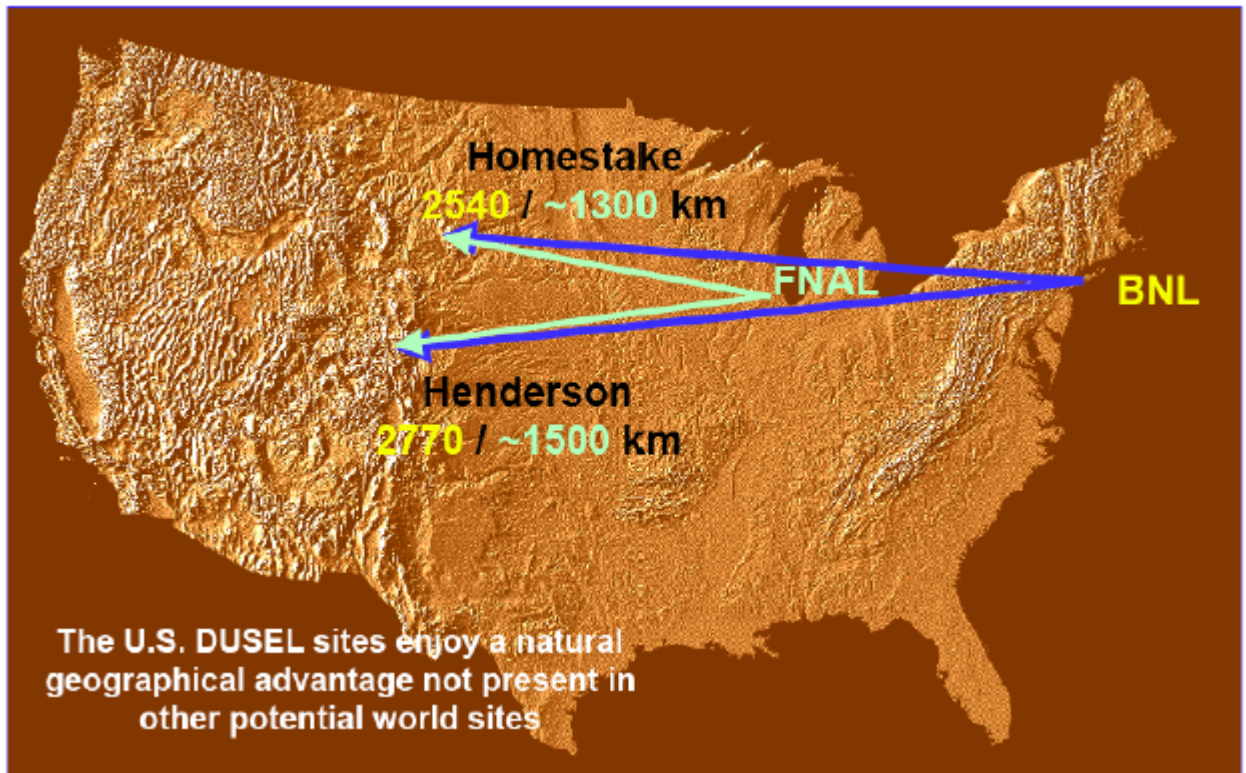
Ideal for long-baseline experiments

Discussions underway (Fermilab and BNL workshop, March 2006)
Lots of challenges, but lots of interest.

A graphical history of neutrino beams (from A. Marchionni)

Neutrino beams power
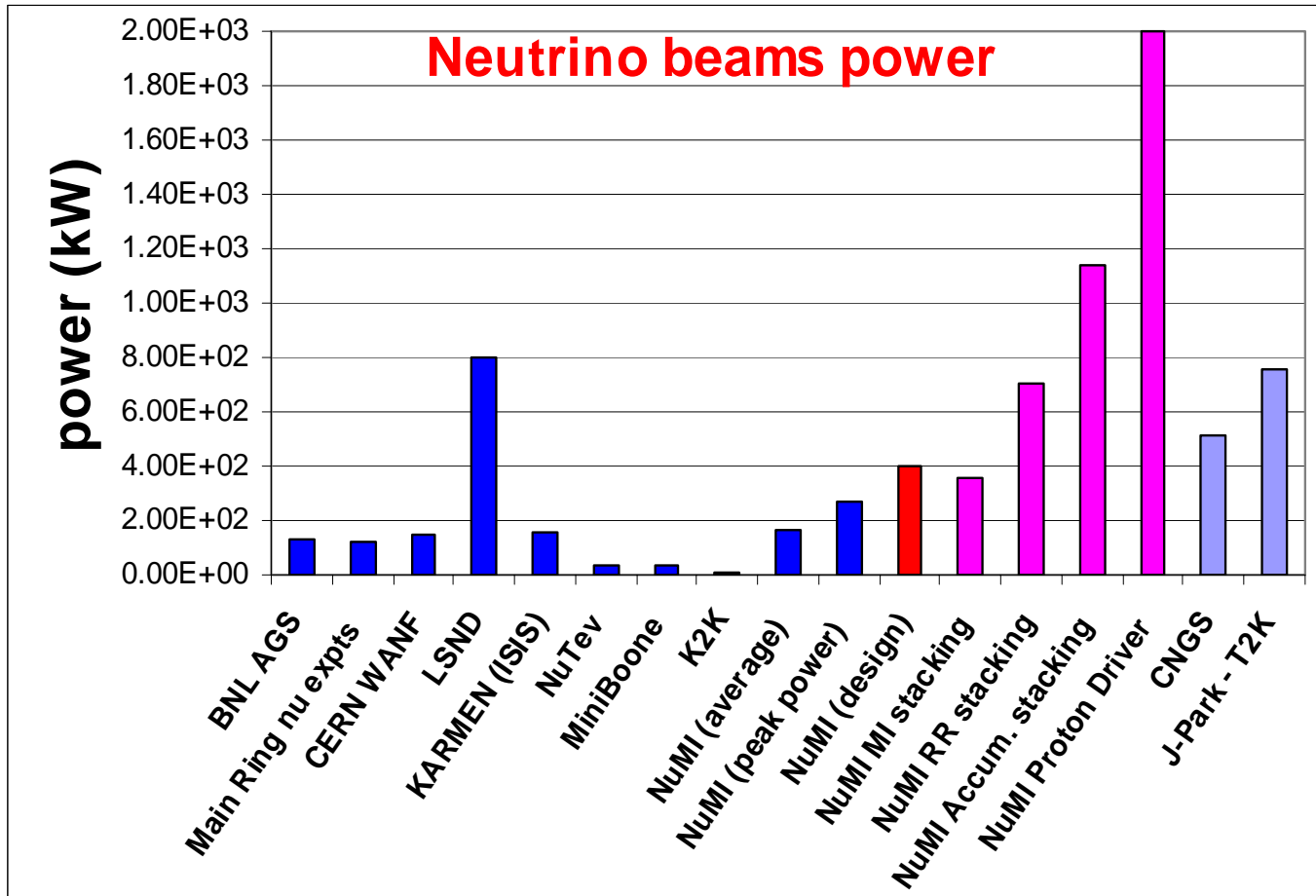
J-Parc: path to a few MW facility is being studied

Recall from lecture 1: neutrinos depend on beam power.
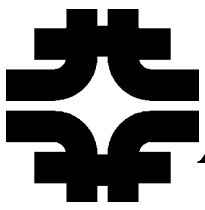
Advanced concepts- Neutrino Factory

A possible layout of a neutrino factory

H⁻ linac 2 GeV, 4 MW — Accumulator ring + bunch compressor

Magnetic horn capture — Target

cooling!

Drift

Phase rotation

target!

Recirculating Linacs 2 → 50 GeV

Linac → 2 GeV

acceleration!

50 GeV

Decay ring – 50 GeV ≈ 2000 m circumference

2 beamlines

ν beam to far detector   ν beam to near detector

2000-06-18 · Peter Gruber, CERN-PS
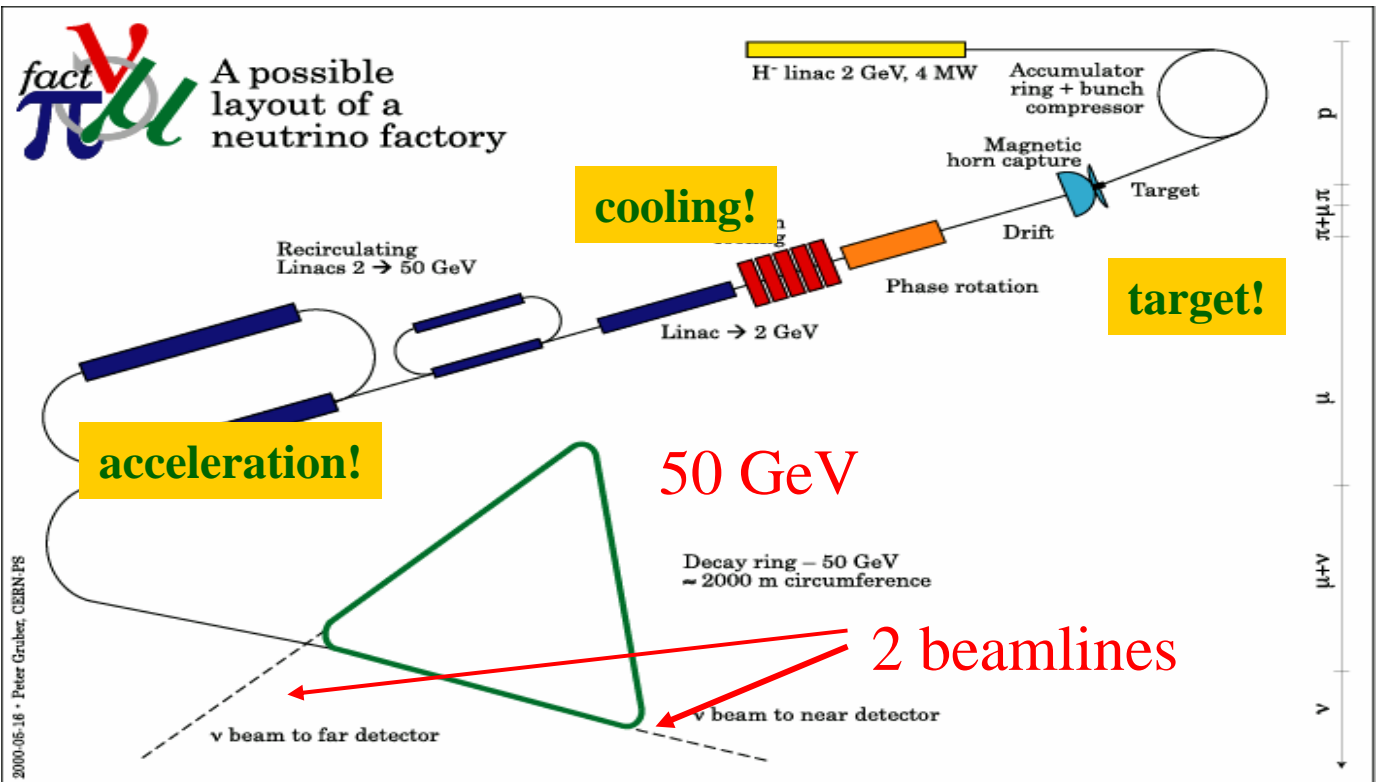
Based on decays of stored muons.   **After Blondel**
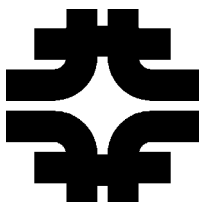
$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$

$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

Muon cooling schemes adopted from μ-collider designs.

Designs produce 1-5x10²⁰ μ decays per year
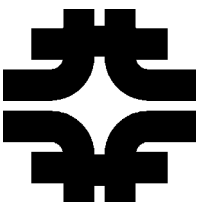
Neutrino Factory Fluxes

Neutrino Fluxes at L = 10000 Km
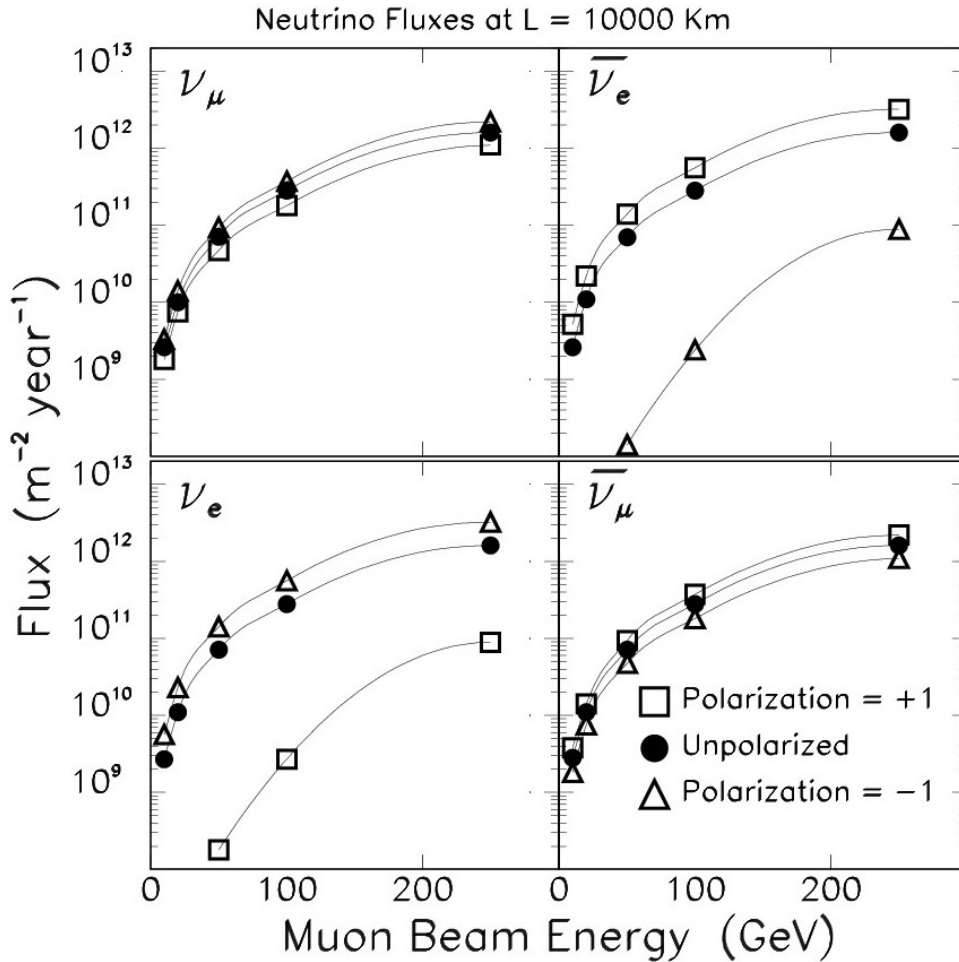
In forward direction

$$F_{\nu_\mu}(x) \propto E_\mu{}^2 x^2 \left[(3-2x) + P_\mu(1-2x)\right]$$

$$F_{\bar{\nu}_e}(x) \propto E_\mu{}^2 x^2 \left[(1-x) + P_\mu(1-x)\right]$$

where $\quad x = \dfrac{E_\nu}{E_\mu} \quad$ and P is the μ polarization

Statistical power of Neutrino Factory

5 Years data taking

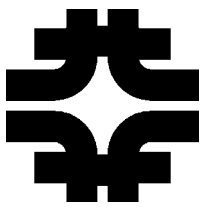| Expt	$\sin^2 2\theta_{13} = 0.1$		$\sin^2 2\theta_{13} = 0.01$	
	Signal	Bkg	Signal	Bkg
MINOS	49.1	108	6.7	109
ICARUS	31.8	69.1	4.5	70.3
OPERA	11.2	28.3	1.6	28.6
T2K	132	22.7	16.9	23.5
NOvA	186	19.7	23.0	20.7
NOvA+FPD	716	75.6	88.6	79.5
NuFact nu	29752	44.9	4071	44.9
NuFact nubar	7737	82.0	1116	82.0

Calculations of W. Winter
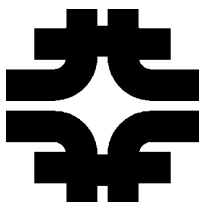
Normal Hierarchy, $\delta = 0$
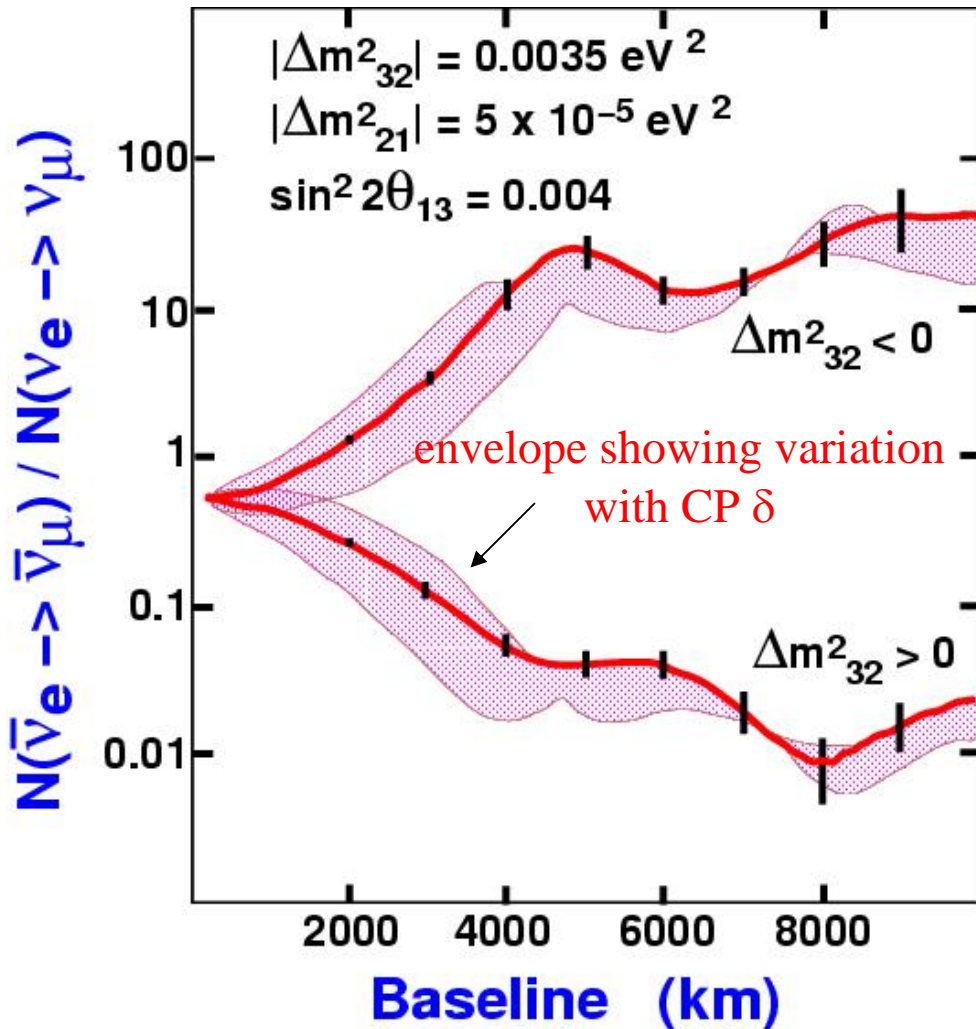
NUFACT: Beam = 3 x 10^{20} decays/yr,
E = 50 GeV, M_{det} = 100 kt, baseline 7300 km

Note this is a large magnetized detector
because signal is "wrong-sign" μ

S. Geer - Erice-04

Neutrino Factory is sensitive to very low sin²2θ₁₃

$|\Delta m^2_{32}| = 0.0035 \text{ eV}^2$

$|\Delta m^2_{21}| = 5 \times 10^{-5} \text{ eV}^2$

$\sin^2 2\theta_{13} = 0.004$

$\Delta m^2_{32} < 0$

envelope showing variation with CP δ

$\Delta m^2_{32} > 0$

y-axis: $N(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) / N(\nu_e \rightarrow \nu_\mu)$

x-axis: Baseline (km)

Ratio of oscillation rates from μ⁻ and μ⁺ vs. baseline

Conditions: 10^{20} μ from 20 GeV ν-factory, 50 kT detector

Barger et al., PRD62, 073002, 2000; hep-ph/0003184
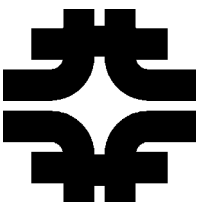
Variation with $\sin^2 2\theta_{13}$, *beam intensity*
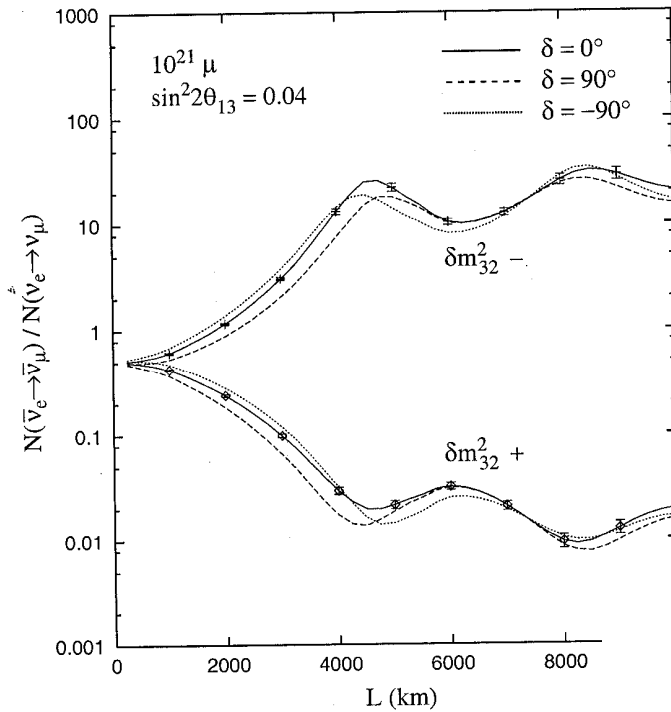
FIG. 10. Same as Fig. 5 except for 10^{21} muo

$\sin^2 2\theta_{13} = 0.04$, 10^{21} muons

Notice these special points
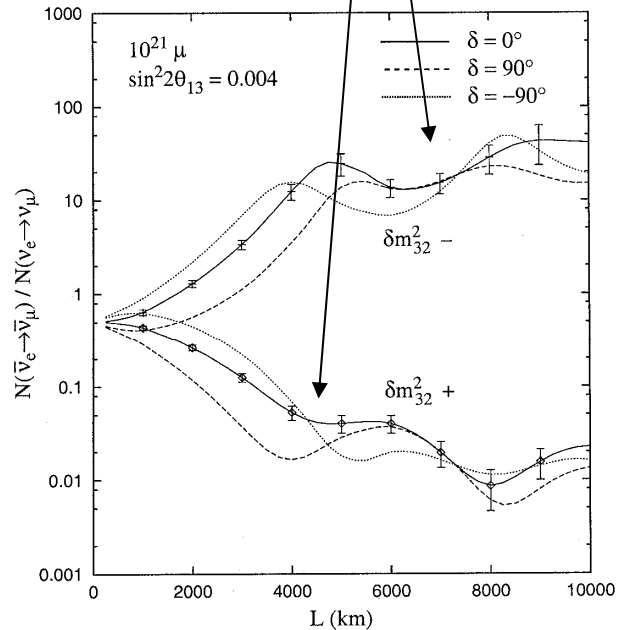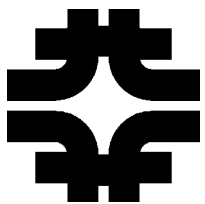
$\sin^2 2\theta_{13} = 0.004$, 10^{21} muons

FIG. 11. Same as Fig. 5 except for 10^{21} muons and $\sin^2 2\theta_{13} = 0.004$.
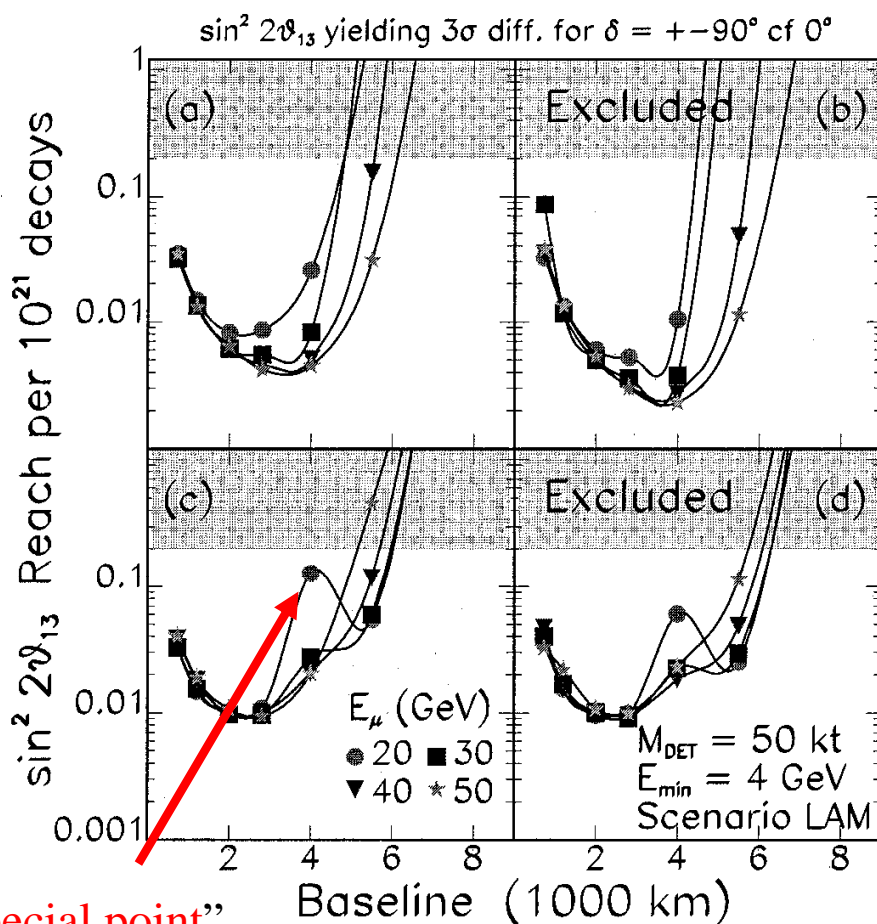
20 GeV ν-factory, 50 kT detector

Barger et al., PRD62, 073002, 2000; hep-ph/0003184

Interplay of mixing strength and baseline for CP determination at a ν-factory

sin²2θ₁₃ reach vs. baseline
for CP discrimination

$\sin^2 2\theta_{13}$ reach vs. baseline for CP discrimination

sin² 2ϑ₁₃ yielding 3σ diff. for δ = +−90° cf 0°

(a) Excluded (b)

(c) Excluded (d)

E_μ (GeV)
● 20 ■ 30
▼ 40 ★ 50

M_DET = 50 kt
E_min = 4 GeV
Scenario LAM

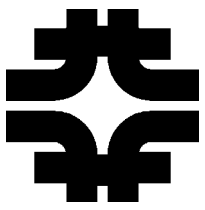sin² 2ϑ₁₃ Reach per 10²¹ decays

Baseline (1000 km)

0, π/2 distinct

0, -π/2 distinct

1st "special point"

normal   inverted

Conditions: 10²¹ μ from 20 GeV ν-factory, 50 kT detector

Sidebar - magic baseline removes degeneracies (that second "special" point)

$$P_{\text{app}} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$$\pm\ \alpha \sin 2\theta_{13}\, \xi \sin \delta_{\text{CP}} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

$$+\ \alpha \sin 2\theta_{13}\, \xi \cos \delta_{\text{CP}} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

$$+\ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},$$
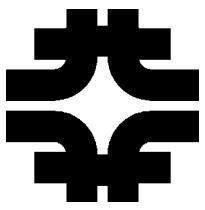
$$\Leftrightarrow\ \sin(\hat{A}\Delta) = 0$$

$$\Leftrightarrow\ \sqrt{2} G_F n_e(L) L = 2\pi$$

$$\Leftrightarrow\ L \sim 7500\ \text{km}$$

Removes CP dependence at this baseline, regardless of conditions.

Best for $\sin^2 2\theta_{13} < 0.01$, where CP degeneracies are largest
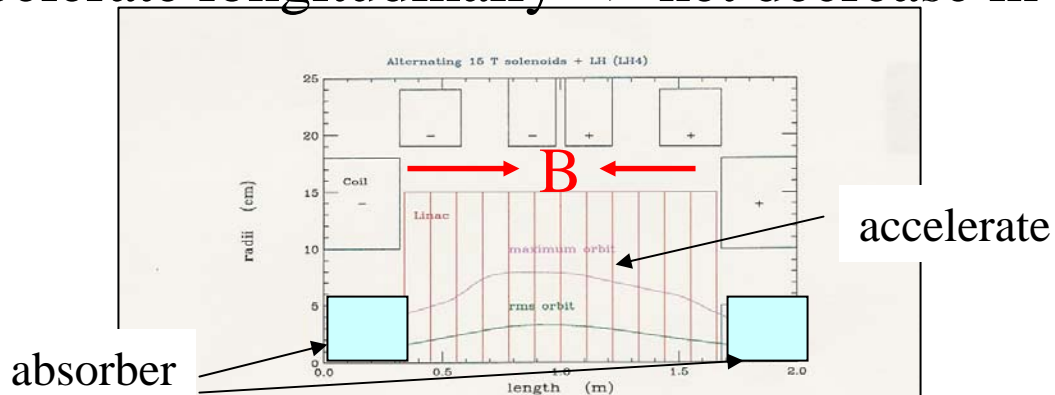
Practicalities - cooling in two directions

μ^+ and μ^- from decays naturally require cooling both in P_T and P_L

Current thinking centers on *ionization cooling.*
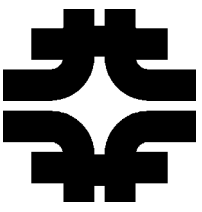
TRANSVERSE COOLING

Reduce momentum uniformly in all coordinates by ionization in a liquid medium (liquid H_2).

Re-accelerate longitudinally –> net decrease in P_T/P_L

Figure 2: Schematic of a 2 m section (one period) of the alternating solenoid transverse cooling lattice described in the text.

Reduction in transverse emittance ε_T

Note ε_T ~ Area of phase ellipse in x, angle space

Longitudinal Cooling
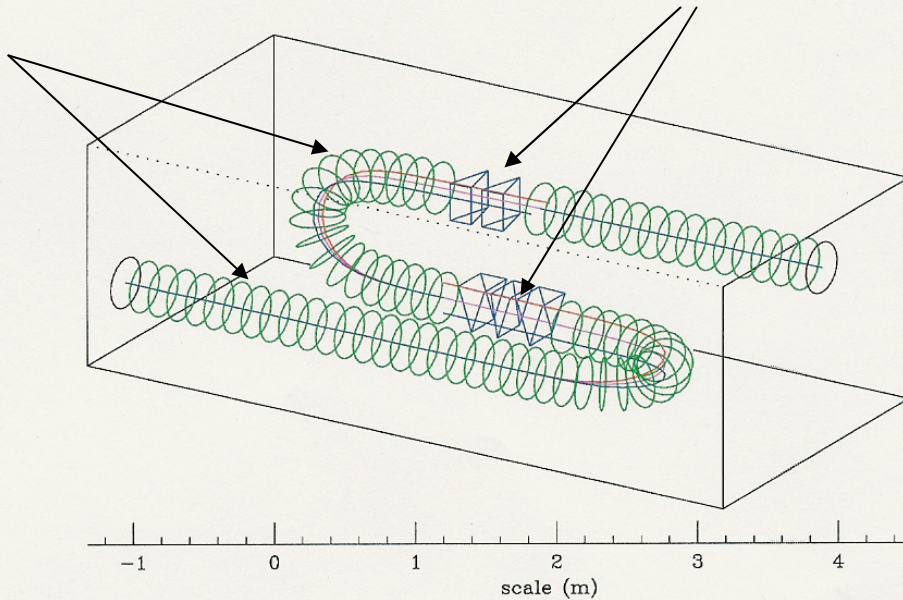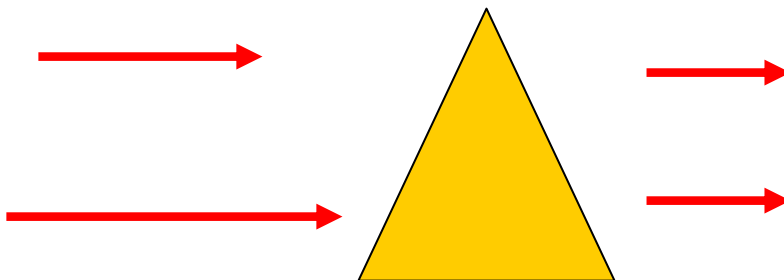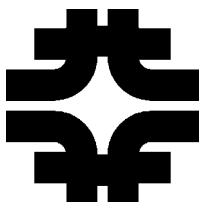
Solenoids

Absorbers

Figure 3: Schematic of the bent solenoid longitudinal emittance exchange section.

Curved solenoids introduce dispersion, e.g.

$$y = f(E)$$

High energy sees more material than low
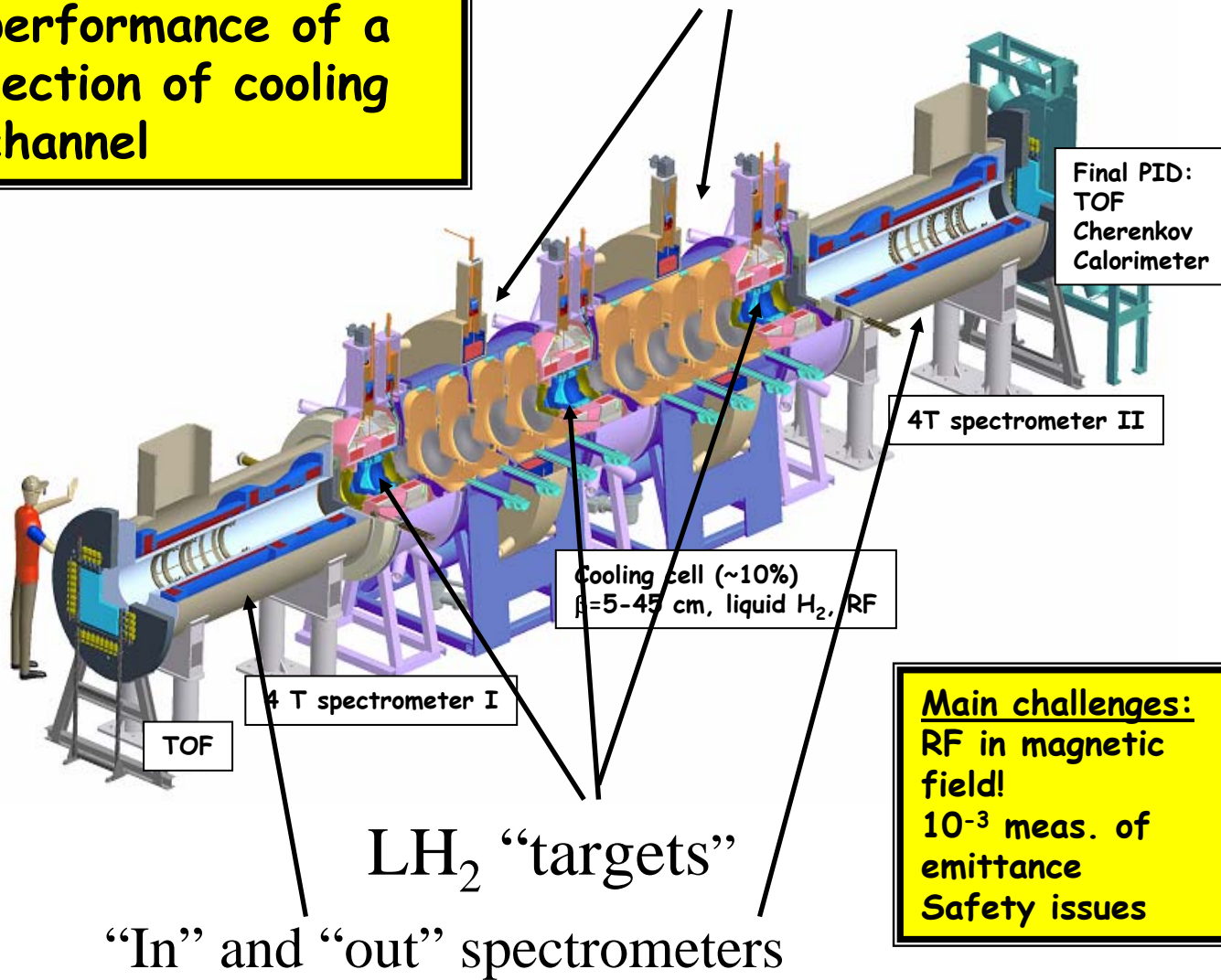==> spread reduced

MICE Experiment at RAL

**Aims:** demonstrate feasibility & performance of a section of cooling channel

RF Cavities

Final PID:
TOF
Cherenkov
Calorimeter

4T spectrometer II

Cooling cell (~10%)
β=5-45 cm, liquid H_2, RF

4 T spectrometer I

TOF

Main challenges:
RF in magnetic field!
10^{-3} meas. of emittance
Safety issues

LH_2 "targets"

"In" and "out" spectrometers

Build a prototype cooling channel

Cool 200 MeV beam by 10%
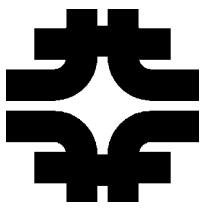
Final Sidebar - Polarization at a neutrino factory

Polarization is defined as $max <\sigma \cdot e> = P$

(e is direction of polarization <u>vector)</u>

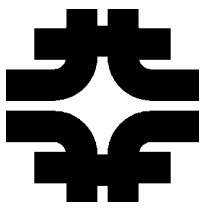In the reaction $\quad \pi^+ \rightarrow \mu^+ \nu_\mu$

the muon polarization is $- v/c = - P_\mu^*/E_\mu^* = - 0.27$

Spin rotation in the magnetic and electric fields of an accelerator has been shown to decrease this to ~18%, unless special steps are taken.

Why interesting? Recall that

$$F_{\bar{\nu}_e}(x) \propto E_\mu^2 x^2 \left[(1-x) + P_\mu (1-x) \right]$$
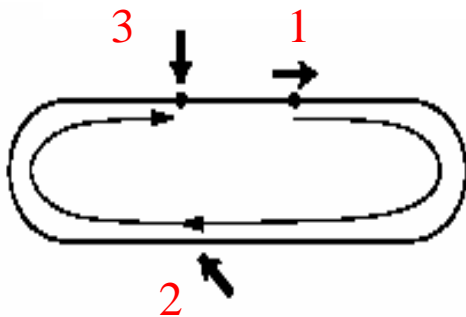
If $P_\mu = 1$, the flux of $\bar{\nu}_e$ vanishes!

Preserving polarization at a storage ring

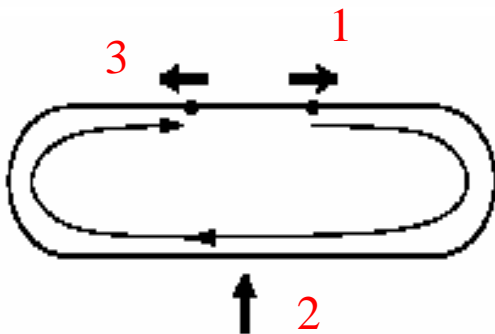Spin tune depends on magic energy (princple of g-2 experiment)

$$\nu = a_\mu \gamma = \frac{g_\mu - 2}{2} \frac{E_{beam}}{m_\mu} = \frac{E_{beam}(GeV)}{90.6223(6)} \ .$$

E = 22.656 GeV
$\nu = 1/4$ "Normal"

E = 45.311 GeV
$\nu = 1/2$ "Reversing"
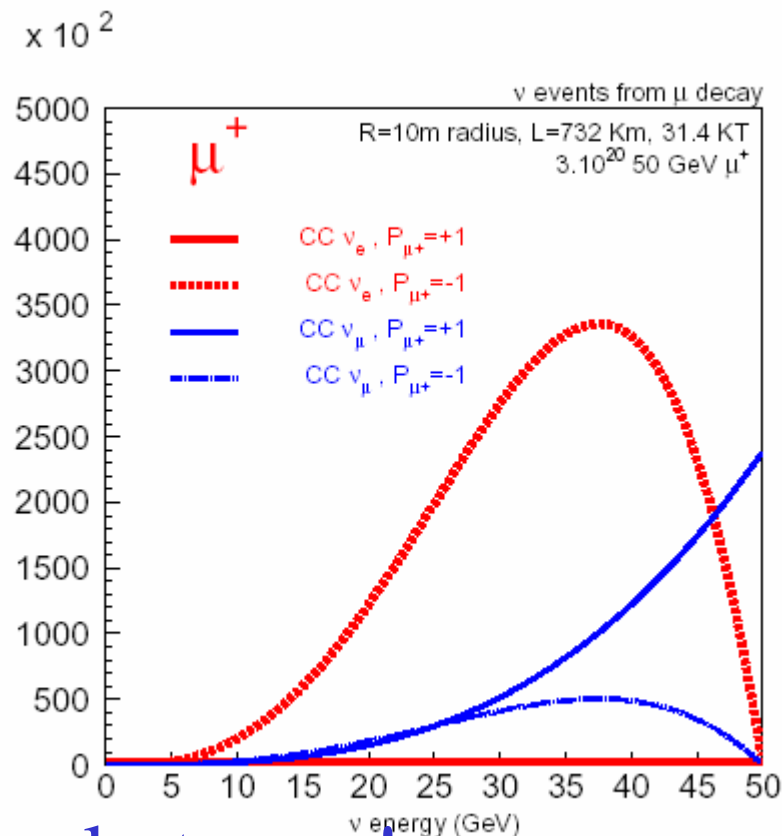
Any Energy
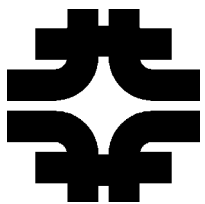$\nu = 0$ "Bowtie" = 2 beams

Graphic: A. Blondel
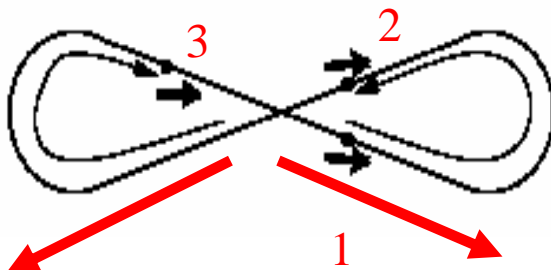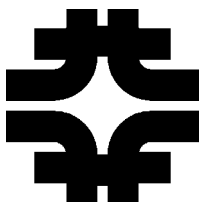
Useful or just for fun?

A.Blondel, "Muon Polarisation in the Neutrino Factory"

. By switching from negative muons with 50% negative polarisation to positive muons with 50% negative polarisation, one can change the ratio of CC ν_e to CC ν_μ by a factor 20, this ratio is only 5 in absence of polarisation. This must be useful.
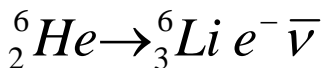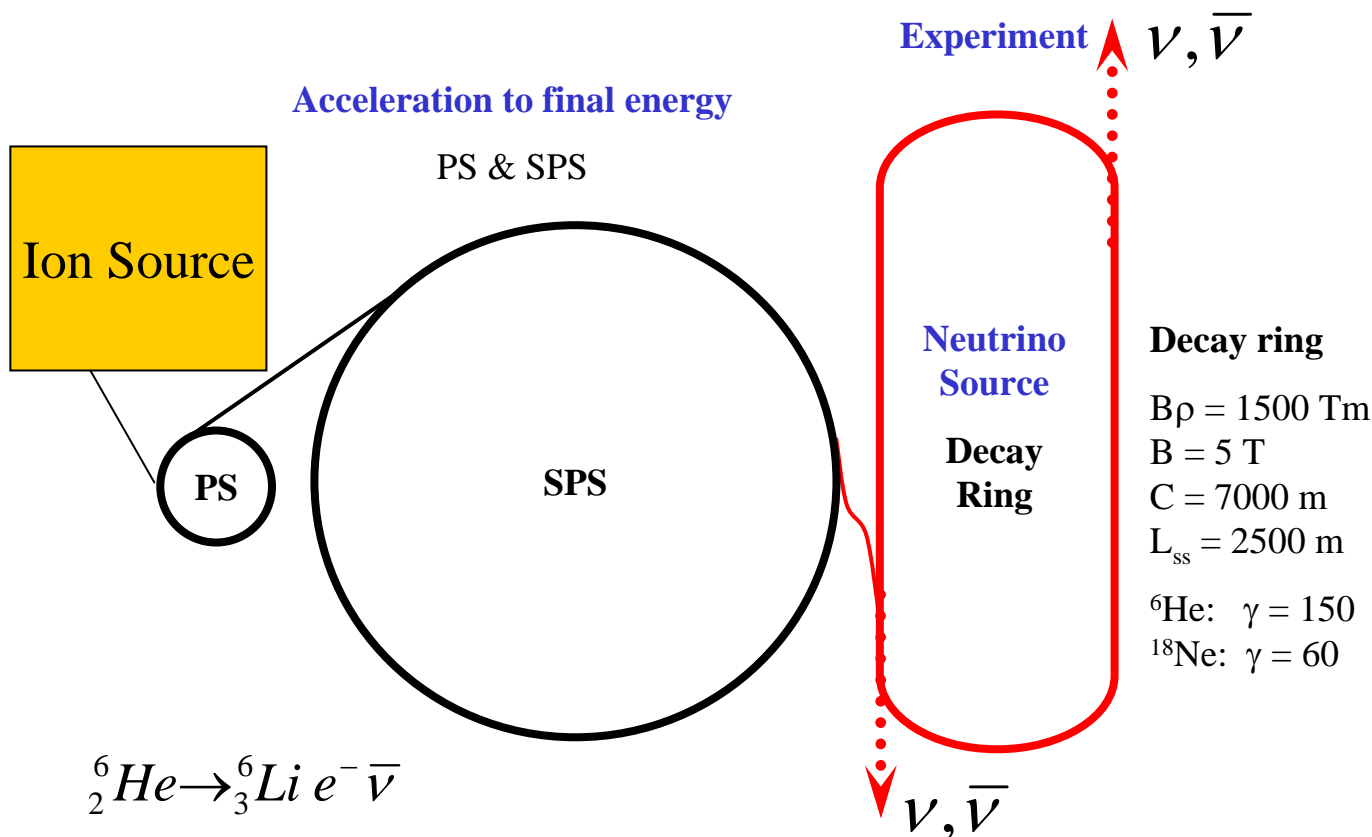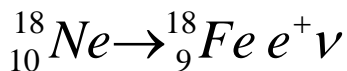

Too early to say!

Beta-beams - an alternative source of clean ν_e and $\overline{\nu}_e$ beams

Acceleration   **Neutrino source**

Experiment $\nu, \overline{\nu}$

Acceleration to final energy
PS & SPS

Ion Source

PS   **SPS**

Neutrino Source

Decay Ring

$\nu, \overline{\nu}$

Decay ring

$B\rho$ = 1500 Tm
B = 5 T
C = 7000 m
L_{ss} = 2500 m

^{6}He: γ = 150
^{18}Ne: γ = 60

$$_2^6He \rightarrow {}_3^6Li\ e^- \overline{\nu}$$

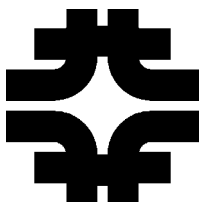Average E_{cms} = 1.937 MeV

$$_{10}^{18}Ne \rightarrow {}_9^{18}Fe\ e^+ \nu$$

Average E_{cms} = 1.86 MeV

Need high γ because energy low.

CERN concept
(for Frejus, 130 km)
(from Lindross, NUFACT 05)

About 10^{18} decays/year

Any relevance of this β-beam concept for Fermilab?

Extraordinarily difficult if it can be done at all

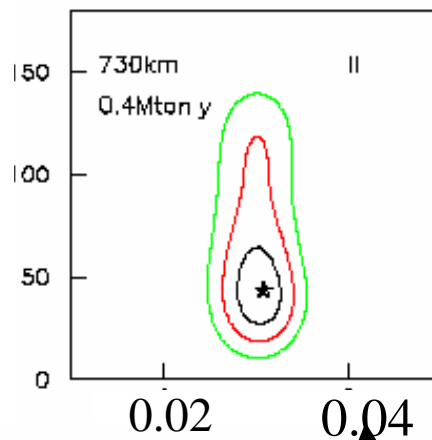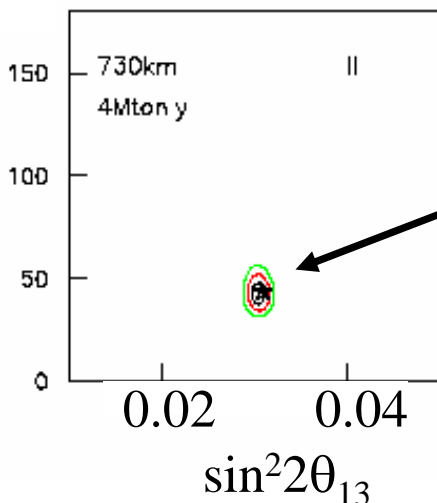Build ion source
Rigourous control of losses (quenching)
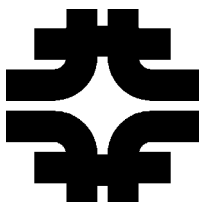Tunnel activation

Discussed in literature, conferences

Distinguish δ from (0,π)

730km
0.4Mton y
II

0.02   0.04

$\sin^2 2\theta_{13}$

Soudan distance with 2 different (large) exposures

730km
4Mton y
II

0.02   0.04

$\sin^2 2\theta_{13}$

High γ gives an advantage that improves competitiveness with combination of conventional "superbeam" experiments

Conclusions - the new world is calling!

These 3 sets of lectures have shown you the details of the first crack in the Standard Model.

Only time and work will tell if this is Joshua's trumpets bringing down the walls of Jericho!
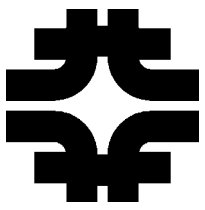
The amount of activity going into understanding, speculating, building and experimenting in the field is prodigious.

Projects, ongoing, building, planning, speculating.

Hope you are now in a position to enjoy this really cool physics.

Participation is the best way!

And, as Stephen Parke or (was it Boris?) said:

Neutrinos are just plain fun!